UK Roadmap-2014: ***Laser-based Manufacturing Applications***

Interim Report, August 2014

UK Roadmap-2014: *Laser-based Manufacturing Applications*

Interim Report, August 2014

CONTENTS

List of Figures

List of Tables

Appendices

UK Roadmap-2014: *Laser-based Manufacturing Applications*

Executive Summary

The primary *objective* of the Roadmapping exercise is to identify new and evolving ***manufacturing applications*** where laser processing may play a significant enabling role, e.g. for high-value-added components and systems and those fabricated from new/mixed engineering materials, or relating to new production techniques. In addition, the aim is to identify relevant areas where ***research and development*** would be required to facilitate future laser-based solutions to such production needs, for example in new laser-material process science and technology, new or enhanced laser source development, beam manipulation and delivery, and system integration/control issues. Such a roadmap must embrace the needs of both UK industry and researchers, including laser-users in manufacturing and those in the technology-supply chain. It could also contribute to the evidence-base for strategic planners and UK funding agencies.

With these objectives in mind, a Roadmapping Workshop was proposed by the EPSRC *Centre for Innovative Manufacturing in Laser-based Production Processes* (CIM-LbPP) and the *Association of Industrial Laser Users* (AILU), and subsequently organised in partnership with the *Institute for Manufacturing (IfM)* at Cambridge University, using Roadmap-Workshop methodologies the Institute had previously developed. The *IfM* also provided the outline Workshop design and led the programme facilitation of the Roadmapping Workshop, which took place on 04 March 2014 in London at the Institute of Physics Headquarters, attracting participants from UK industry, academia and the public sector.

From a pre-Workshop independent information gathering stage and subsequent work on the day, the *key market and industry drivers and needs* were identified as the following:

- New laser and machine processing capabilities to enable processing of dissimilar, advanced or brittle materials as well as integrating various processes into one laser system;
- Cost reduction of laser-based manufacturing hardware, including maintenance and lifetime cost of ownership to respond to global financial pressures;
- The need for automation and real time decision making to enable product customisation;
- The development and deployment of improved/new lasers including high power and tuneable lasers, picosecond (ps), and femtosecond (fs) lasers.
- Systems with reduced environmental impact via decreased energy consumption of laser tools, lighter and stronger structures for laser systems; reduced material utilisation and production waste.

Roadmapping Workshop Conclusions

The **priority** *laser-based manufacturing application areas* identified were predominantly around manufacturing techniques that are applicable to a variety of products and markets as follows:

- Additive Manufacturing including Repair;
- Joining materials including both thin and thick, similar and dissimilar materials;
- Surface processing and modification;
- Micro-manufacturing.

The most important underpinning *technologies* and *R&D priorities* required to deliver these application techniques were identified as:

- Fundamental laser process science to improve the understanding of laser-material interactions and eliminate the "black art" associated with some current processes;
- Development of better process output monitoring, analysis and control;

- Development of improved and new lasers and laser systems as well as their integration into machines, tools and equipment;
- Improvements of the laser beam delivery and control to enable better manufacturing precision and speed;
- Development of better and more sophisticated, high speed scanners and scanning systems.

The UK was seen as strong in solid state and fibre laser technologies, with highly-rated academic laser research and expanding commercial laser companies. The UK is also highly capable in research areas underpinning the development of next generation lasers and laser systems such as optics, modelling and simulation, sensors, analysis and monitoring systems.

The low UK market take-up/demand for laser-based systems in manufacturing (e.g. compared to Germany), which is evident across diverse areas of UK industrial engineering appears to indicate a low level of appreciation of the commercial benefits of these technologies, and is identified as a key focus area for future strategic planning.

Future Action

The next step in the Roadmapping exercise is to distribute this Interim Report on the outcomes of the Roadmapping Workshop to the broader UK Laser Materials Processing community to provide an additional round of consultation to help produce a definitive UK Roadmap-2014 for Laser-based Manufacturing Applications.

The dissemination of this Interim Roadmapping Report is accompanied by a Consultation Template, which is aimed at facilitating the collection of a broader range of inputs from across our community on the key outcomes of the Workshop. As far as possible, opinions gathered in this way will be incorporated in a subsequent final UK Roadmap-2014 for Laser-based Manufacturing Applications.

UK Roadmap-2014: *Laser-based Manufacturing Applications*

1.0 Introduction

A key outcome of the Workshop on Laser Materials Processing (LMP) held at Farnham Castle in February 2012 [1] was a widely-shared recognition of the need to produce a UK Roadmap, relating both to laser-based manufacturing applications/markets and future requirements for technologies and hardware. It was agreed that such a document would need to have relevance for UK companies and researchers (including laser-users in manufacturing and those in the technology-supply chain), as well as contributing to the evidence-base for strategic planners and UK funding agencies.

To achieve this goal, the Association of Laser Users (AILU) partnered with the *EPSRC Centre for Innovative Manufacturing (CIM) in Laser-based Production Processe*s (CIM-LbPP) with the aim of coordinating inputs from both industrial and academic sectors of the UK laser-based manufacturing community. In planning the production of a UK Roadmap, the support and encouragement of the Department for Business, Innovation and Skills (BIS) and the Electronics, Sensors and Photonics Knowledge transfer Network (ESP KTN) are gratefully acknowledged. Moreover, there is recognition that we are not starting from scratch, since in addition to the Farnham Report [1] there are also Europe-wide Photonics21 Roadmaps [2], to which many in the UK community have contributed.

Objectives

The primary *objective* of the Roadmapping exercise is to identify new and evolving ***manufacturing applications*** where laser processing may play a significant enabling role, e.g. for high-value-added components and those fabricated from new/mixed engineering materials, or relating to new production techniques.

In addition, the aim is to identify relevant areas where ***research and development*** would be required to facilitate future laser-based solutions to such production needs, for example in new laser-material process science and technology, new or enhanced laser source development, beam manipulation and delivery and system integration/control issues.

Thus, the Roadmap output should provide foresight information relating to one or more of the following:

1. new or enhanced manufacturing processes, industrial applications and markets;
2. new or enhanced laser-based manufacturing systems and markets;
3. new or enhanced key system components (e.g. new lasers) and market sectors

A more generic aim is to try to stimulate a larger scale of commercial laser-based activity in the UK manufacturing sector, where UK industrial laser source and system manufacturers continue to suffer from a generally weak home market, driving them to export a very large fraction (frequently >95%) of their production. Moreover, it is relevant (and chastening) to note the low-level of recognition across large swathes of UK industry of the technical benefits and commercial opportunities which laser/photonics-based techniques offer to manufacturing across many industry sectors. This is spectacularly exemplified in a recently-published report [3] on technologies key to the future health of high value manufacturing in the UK produced by a Foresight Team working under the auspices of the UK Government Office for Science.

Far from highlighting the production opportunities of laser-based manufacturing processes, as for example in EU *Factories of the Future* documentation [4], or in relevant US documents [5], laser-based technologies warranted not a single mention in this 250+ page UK Report.

So, whilst fully recognising the global scale of this business, an important objective for the UK industrial laser community is to alert a larger fraction of UK manufacturers (as well as UK government industrial policy makers) to the powerful enabling features of laser-based processes in manufacturing across diverse sectors of industry, and particularly at the high-added-value end of the market.

2.0 Development of *UK Roadmap-2014*

The generation of an effective Roadmap demands the integration of technical, strategic and market inputs from as broad a distribution as possible of active professionals drawn from the UK industrial laser-based manufacturing community, with representation from both the industrial and academic sectors.

In an effort to achieve as large and diverse a set of inputs from across the UK community as possible within a reasonably structured set of activities, a multi-step process was conceived as follows:

- One-Day Roadmapping Workshop and Interim (Draft) Roadmap Report;
- Process of consultation with the UK Industrial Laser Community;
- Production and dissemination of the Final UK Roadmap-2014 Report.

The key element in the formulation of a draft UK Roadmap was the *One-Day Roadmapping Workshop*, for which a three-phase ***Methodology*** was employed as follows:

1) **Pre-Workshop** Workshop Design and Information Gathering,
2) **The Workshop** One-Day Roadmapping Workshop,
3) **Post Workshop** Data Compilation and Interim Report

2.1 Methodology: Workshop Design and Information Gathering

Aims and Desired Outputs

The primary aim of the Roadmap exercise is to use the foresight and professional skills of the UK community to identify new and evolving manufacturing applications and growing markets, where laser-based manufacturing technologies may play a key role in achieving technical and commercial success. In seeking such information, the methodology that was adopted sought to generate outputs via a process of gathering independent inputs from industry professionals regarding their opinions on key future important manufacturing applications and markets, as well as the key factors which drive market growth and industry expansion in these industries. For any application or market, it is also crucial to identify the criteria which define the scale and probability-of-success of a given opportunity, as well as to recognise the criteria which delineate the technical and commercial feasibility that a given opportunity can realistically be exploited.

Workshop Attendees

In planning this event, the team from AILU and CIM-LbPP received advice and guidance from the *Institute for Manufacturing (IfM)* at Cambridge University, who had previously organised many similar Roadmapping events and count branches of government and multiple companies among their impressive client list. The experience of *IfM* professionals with this type of Workshop strongly suggested a limit for on-site participation of about 30, and this roughly matched the facilities available at the available London location at the Institute of Physics Headquarters. Faced with this difficult selection task, the (AILU/CIM-LbPP) organising team sought to produce an attendee list with the following criteria:

- A majority of industrial colleagues - with a target industry/academia ratio of 4:1,
- A balance between laser 'users' and those in the hardware supply chain, and
- A broad experience balance.

Fortunately, a large fraction of invitees were able to attend, with only a few not available due to diary conflicts; the final list of Workshop Attendees is shown in **Appendix A**. Moreover, efforts were made to include non-attendees and attendees alike in a ***pre-Workshop 'Homework Stage'***, so that a significantly larger fraction of the UK LMP community could contribute even at this early stage. Thus in parallel with distribution to Workshop participants, the slide-set 'homework' templates were also emailed to more than 100 industry professionals from the AILU data base.

Workshop Architecture and Pre-Workshop Work Templates

As indicated, a set of three homework slides, reproduced below, was emailed to all attendees (and >100 non-attendees) with instructions to return the completed slide-templates in time for pre-Workshop compilation of the data, to gather independent participant inputs. Some brief Guidance Notes (reproduced as **Appendix B**) and including the Workshop Agenda were sent with the 'homework'.

Slide 1 Requested participant opinion of the top two *Market and Industry Drivers* and the most important *Manufacturing Applications* of laser-based technology over the next three, seven and ten year periods (see Figure 1);

Slide 2 Requested participant opinion of the top five criteria from a prescribed list defining a market *opportunity* for a given manufacturing application (see Figure 2);

Slide 3 Requested participant opinion of the top five criteria from a prescribed list defining the *feasibility* of a given manufacturing application (see Figure 3).

The inputs (votes) from Slides 2 and 3 were collected (by email) and consolidated by the *IfM* team. Then the criteria that collected the most votes were set up to be used during the Workshop to prioritise from the full list of suggestions provided on Slide 1 for drivers and applications.

Having agreed its final 'design', the *IfM* team used the week prior of the Workshop to cluster all the received input data, and to prepare the collateral material required for use on the day including facilitation PowerPoint slides, large printed wall-posters and participant hand-outs.

Slide 1

Laser-based Manufacturing Applications – Roadmapping Workshop

Name: Organisation:

Timeline	**Short** (3 years)	**Medium** (7 Years)	**Long** (10 Years)
Market and Industry Drivers	1. … 2. …	1. … 2. …	1. … 2. …
Manufacturing Applications	1. … 2. …	1. … 2. …	1. … 2. …
Required system Hardware	This section to be completed during the workshop		

Workshop initiated by EPSRC Centre for Innovative Manufacturing in LASER-BASED PRODUCTION PROCESSES; the association of AILU laser users

Supported by EPSRC Pioneering research and skills; BIS Department for Business Innovation & Skills

Figure 1: Slide one of the Pre-Workshop Set of Three Homework Templates.

Slide 2

Factors for Opportunity

DIMENSION	FACTOR	DEFINITION
VOLUME	Market size	Size of potential market, or number of potential adoptions, reasonably available to us.
	Our sales potential in a given time	Sales volume or number of adoptions anticipated in a defined time (say, 5 years)
	Synergy opportunities	Possible additional benefits to other projects or activities; or the possibility of new opportunities in combination.
	Customer benefit	Identifiable benefit to customers (internal or external) or potential adopters
	Competitive intensity in Market	Number or significance of the competition
MARGIN	Increased margin, or benefit per unit	Improvement in product margin (eg by cost reduction or price premium) compared to existing products; or benefit to us per adoption
	Business cost reduction or simplification	Facilitates cost reduction or simplification of business processes
	Industry/market readiness	How easy will it be for customers or adopters to take up the product; do they have to change their behaviour or processes?
PLATFORM FOR FUTURE BENEFIT	Market growth	Anticipated growth rate of market
	Future potential	Product is a platform for future products or could open new markets in future
INTANGIBLES	Learning potential	Will improve the knowledge or competence of the business
	Impact on Brand Image	Effect on Brand image or staff morale
	Impact on key customer relations	Importance for relations with key customers

Figure 2: Slide two of the Pre-Workshop Set of Three Homework Templates.

Slide 3

Factors for Feasibility

DIMENSION	FACTOR	DEFINITION
CHARACTERISTICS OF THE APPLICATION/PROCESS OR PRODUCT	Application/Process or Product differentiation	How well the application/process or product is differentiated from those of major competitors
	Sustainability of competitive advantage	Our ability to sustain competitive position (eg IPR, Brand strength etc), using the Application, Process or product
	Technical challenge	How confident are we that the proposed Manufacturing application/Process or Product is technically feasible?
	Market knowledge	Our understanding of size and requirements of the market that the Manufacturing process or Product will enable
CAPABILITY	Technical capability	Do we have the required technical competence to implement the manufacturing application/ process or design the product?
SUPPORTING BUSINESS PROCESSES	Fit to sales and/or distribution capacity	Fit to our sales competences and/or distribution chain
	Fit to manufacturing and/or supply chain	Ability to exploit new manufacturing process or supply the new product
	Finance	Availability of finance for the project
ORGANISATIONAL BACKING	Strategic fit	How well does the proposal new manufacturing process or product fit our company strategy?
	Organisational backing	Level of staff or management backing at an appropriate level

Figure 3: Slide three of the Pre-Workshop Set of Three Homework Templates.

2.2 Methodology: One-Day Roadmapping Workshop

The One-Day Workshop took place on 04 March 2014 at the Institute of Physics HQ in Portland Place, London. The event design and application of roadmap methodology to the specific case of the *Laser-based Manufacturing Applications* field was led by Dr Nicky Athanassopoulou from the IfM who, along with her colleague John McManus, facilitated the event on the day, ably assisted by Veronica Ferguson and Alex Peden from the CIM-LbPP team, and Karen Brakspear from EPSRC and Louise Jones from the Knowledge Transfer Network.

The day began with introductions of all present, a short background presentation from Professor Duncan Hand (*CIM-LbPP Director*), and an overview of the programme for the day from Dr Athanassopoulou and John McManus.

The main activities are summarised as follows (for full Programme, see **Appendix C**):

1. ***Homework – Slide 1:*** The Workshop commenced with 2-minute presentations from each participant, summarising individual, independent views of (a) the most important *Market and Industry Drivers* over the short-term (3 years) medium-term (7 years) and long-term (10 years), and (b) the most important future laser-based *Manufacturing Applications*.
2. ***Homework – Slides 2 and 3:*** A discussion of the remainder of outcomes of the Homework assignment aimed at producing an agreed set preferred criteria to be used to prioritise the overall list of Manufacturing Applications;
3. The agreed criteria were then used as each participant individually cast three votes (from the full collective list) to create a short-list of the most promising manufacturing applications to be subject to further exploration later in the day;
4. In the afternoon session, *four groups* were created to explore in more depth the short-list of manufacturing applications, and to identify the required technology developments, most important R&D priorities and any anticipated opportunities for collaboration;
5. Finally, the common research themes emerging from the shortlisted laser-based manufacturing applications were identified;

2.3 Methodology: Electronic Data Compilation and Interim Report

The final component of the Workshop was the compilation and transcription of all outputs from the activity of the one-day event into an electronic format including some data analysis of the content.

This information was then compiled in a document [6] prepared by the Cambridge IfM Team, which has been used extensively in preparing the final sections of this Interim Report.

3.0 Outputs from Roadmapping Workshop

3.1 Overview

A total of 36 people contributed to the Workshop including 26 from industry, 6 from universities, and 3 from government, of whom 29 attended the Workshop, plus 6 Facilitators as mentioned in Section 2.2.

As indicated, the Roadmap was designed to include two broad layers:

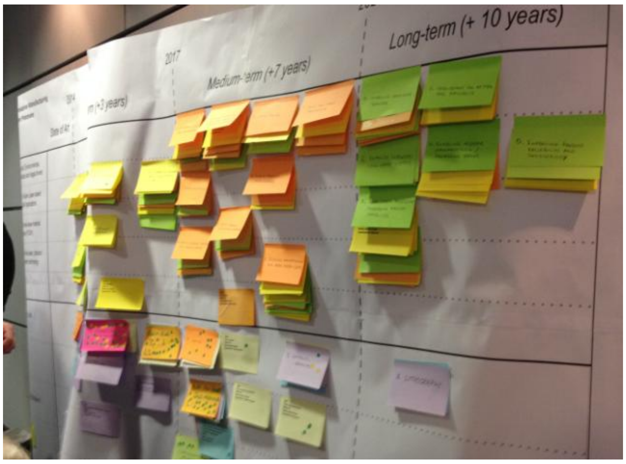
1. Market and Industry drivers, and
2. Laser-based manufacturing applications,

with projections over short- (2017), medium- (2021) and long-term (2024).

The market and industry drivers were further subdivided into the following strands:

- Macroeconomic drivers such as social, technological, environmental, economic, geo-political and legal;
- Industry needs for future laser-based manufacturing applications;
- Industry needs for new laser-material interaction processes;
- Industry needs for new lasers, photonic components and system technology.

Overall a total of 24 distinct market and industry drivers were identified, broadly distributed over the short, medium and long term. Most were either from the ***macro-economic environment*** or relating to future ***industry needs*** for laser-based manufacturing applications and new laser-material interaction processes. The data shows that the drivers and requirements identified for *new laser-material interaction processes*, *new lasers, new photonic components or new system technologies,* are aimed more at medium to long term.



In total 51 laser-based manufacturing applications were identified with over 80% of those in the short and medium term, with ~40% of the proposed applications were focussed on laser-based manufacturing techniques required for emerging engineering materials and material combinations.

The laser-based manufacturing applications were also subdivided into the following layers:

- New laser-based manufacturing applications;
- Enhancements of current laser-based applications;
- Applications for which a specific (new) laser-based process is required to implement new production technology
- Applications for which new engineering materials and material combinations require new laser-based manufacturing techniques
- Other

A schematic Summary of the Roadmap prior to prioritisation is shown in Figure 4.

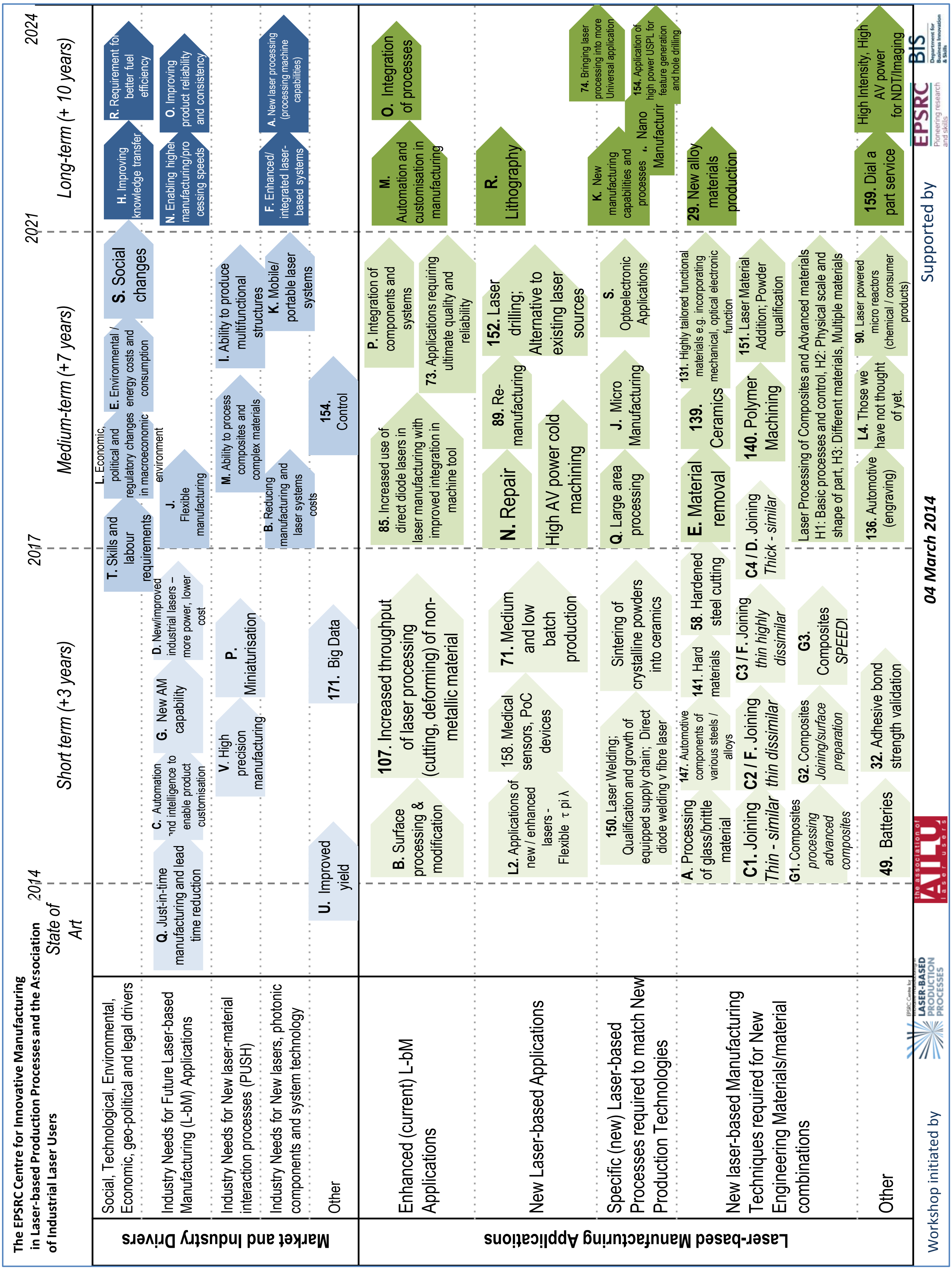


Figure 4: Summary of the Overall Roadmap Prior To Prioritisation

3.2 Market Drivers and Needs

Opinions on the most important industry drivers and needs collected from contributors in advance of the workshop were clustered into common groups. Then depending of the number of contributions (frequency) per group, a prioritised list of the market drivers and needs was developed, as shown in Table 1.

The results showed that of these submissions, the top five-rated market and industry drivers and needs were:

A. New laser and machine processing capabilities to enable processing of dissimilar, advanced or brittle materials as well as integrating various processes into one laser system.

B. Reduction of laser manufacturing systems costs including maintenance, finance etc. (overall cost of ownership) over the laser systems lifetime to enable companies and organisations to respond better to global financial pressures.

C. The need for process automation (real time monitoring, adaptive control and process algorithms). This was considered as a key enabler to mass product customisation (e.g. fashion items, Ultrabook laptops) as well as highly individualised components and products.

D. The development and deployment of improved and / or new lasers including tuneable and high power lasers; picosecond (ps) and femtosecond (fs) lasers; lasers with enhanced properties (e.g. brightness, selectable pulse duration, locking, beam manipulation etc.); low-cost, high power diode lasers with dense wavelength division multiplexing (HPDL DWDM); Multipurpose lasers with high degree of flexibility but high precision.

E. The need to reduce environmental impact by reducing the energy consumption of laser tools, producing lighter and stronger structures and improving laser-based manufacturing processes to reduce material utilisation and production waste.

The 'letter designations' (A, B, C etc.) are also used as indicators in Figure 4.

Table 1: Prioritised list of Independently Selected Market and Industry Drivers

	Group	Detail of Driver or Need	Time-frame	Layer in the roadmap	Freq.
A	**New Laser Processing / Processing Machine Capabilities**	High precision prototypes by laser sintering; Welding dissimilar materials, metal to ceramic/glass; Combining processes, i.e. cut/weld and mark piece in one op rather than two machines; Stress-free optical bonding for beam and image transmission; Reduced distortion and heat affected zones; Athermal materials and reduce outgassing; Wider range of standard processing conditions, High-efficiency beamshapers for high-power CW and high fluence ns and ps pulse applications; Elimination of scrap by dynamic control of the laser based processes; Comparison of SS and CO2 lasers for HP welding.	Short to Long	New Material Processing	**19**
B	**Reducing Manufacturing and Laser System Costs**	Reduction in manufacturing costs; Automated manufacture; Speed of manufacture; Lower ownership-cost of laser-based machines; Cost reduction by fabrication of complex structures; Reduced cost; Product by better use of materials & processing costs; Reduced equipment costs; Reduced maintenance costs; Lower ownership-cost of laser-based machines; Low lifecycle cost of laser system technology; Reduce "photon cost"	Short to Medium	New Lasers and Components	**19**
C	**Automation and Intelligence to**	Elimination of manual alignment; Fully automated intelligent processing; Increasing impact of real-time process control; Adaptive control and	Medium to Long	Future Laser-Manuf Apps	**17**

	Group	Detail of Driver or Need	Time-frame	Layer in the roadmap	Freq.
	Enable Product Customisation	process algorithms; Remote access; Trend towards mass customisation of products e.g. fashion items, laptops; True mass customisation enabled by highly flexible laser-based manufacturing systems (pulse length, wavelength, material handling etc.); Highly individualised components/products			
D	**New / Improved Industrial Lasers - More power, lower cost**	Tuneable power lasers; Laser with enhanced properties (e.g. brightness, pulse durations etc.); Reduced energy consumption (source & process) Low-cost HPDL DWDM, phase locking, beam manipulation; Easier deployment of ps and fs system à Conventional and beamshaping optics for high average power, high reliability ps and fs use; Fibre delivery of ps and fs pulses; Laser sources development; Multipurpose lasers with high degree of flexibility but high precision	Short to Long	Future Laser-Manuf Apps	**12**
E	**Environmental / Energy Costs & Consumption**	Reduced environmental impact e.g. low chemical waste; As energy costs increase, low energy consumption of laser tools advantageous to conventional tools; Environmental – lighter and stronger structures; More electrically efficient laser sources and systems Resource efficiency = <material utilisation, <energy; Environmental issues influencing design parameters & manufacturing process efficiency	Short to Long	STEEPLE	**10**
F	**Enhanced / Integrated Laser-based Systems**	Integrated electronics in other parts/devices; Integration of lasers in robotic machine tools; Microelectromechanical systems; Integrated solutions; Sensors & QA	Long	Future Laser-Manuf Apps	**6**
G	**New AM capability**	AM developments for small /medium size aero / auto components; AM for large and multi-material components; Larger volume and faster build rate additive layer; Stress management for AM processes; Low cost AM processes allowing for medium volume manufacture	Long	Future Laser-Manuf Apps	**6**
H	**Improving Knowledge Transfer**	Transition of knowledge to industry, confidence building; Quick response to industry needs (companies & technology); Wider engagement with manufacturing industries having UK-strength; Wider & deeper engagement with Photonics 21 policy making & projects; Lasers, systems & tech development for non-UK strength manufacturing applications worldwide	Short to Medium	Other	**6**
I	**Ability to produce Multifunctional structures**	Multifunctional structures; Large area micro-surface texturing (functional surfaces); Improved product performance; Greater functionality in product produced by LMP feature generation	Medium	Industry Needs for New laser-material interaction processes	**5**
J	**Flexible Manufacturing**	Flexible tooling; Flexible manufacturing; Flexible and application-specific processing conditions à Application-specific beamshapers for high-power CW and high fluence ns and ps pulse applications	Short to Medium	Industry Needs for Future Laser-based Manufacturing Applications	**5**
K	**Mobile / Portable Laser Systems**	Portable compact robust lightweight laser systems; Lightweighting; Cost-effective, local "at the place" manufacturing / customisation / modification; Localised manufacturing	Medium to Long	Industry Needs for Future Laser-based Manufacturing Applications	**5**
L	**Economic, Political &**	US Govt. regulations making identifier coding marking mandatory e.g. medical equipment; Re-industrialisation of Europe. EU goal to increase	Medium	STEEPLE	**5**

	Group	Detail of Driver or Need	Time-frame	Layer in the roadmap	Freq.
	Regulatory Changes in Macroeconomic Environment	current industry GVA from 16% to 20% by 2020; Political drive & policies promoting UK Manufacturing; Economic sustainability of UK manufacturing			
M	**Ability to process Composites & Complex Materials**	More complex materials and combinations (welding and cladding); Advanced materials; Composite material use in lightweight vehicles	Medium	Industry Needs for New laser-material interaction processes	**4**
N	**Enabling higher manufacturing / processing speeds**	Improved speed in laser based manufacturing; Increase speed/lower cost - Parallel processing, high speed scanning etc.; Higher throughput for short-pulse systems à High damage threshold components for ns and ps pulses	Short	Industry Needs for Future Laser-based Manufacturing Applications	**4**
O	**Improving Product Reliability & Consistency**	Consistency of manufacture; Environmental – reduced remanufacturing by increased component lifetime in service; Lower cost, more reliable lasers	Short	Industry Needs for Future Laser-based Manufacturing Applications	**4**
P	**Miniaturisation**	Medical device miniaturisation – to the extent that 'robotic' nanoscale MEMs for insertion into bloodstream, etc.; Reduced feature size in semicon EUV pump sources; Miniaturization - smaller features, Higher accuracy, Minimal damage & dross plus shorter wavelength, ultra short pulses	Medium to Long	Industry Needs for Future Laser-based Manufacturing Applications	**4**
Q	**Just in Time Manufacturing & Lead time Improvement**	Just in time; Lead time; Unpredictable demand = supply chain agility = <time enquiry to delivery	Short	Industry Needs for Future Laser-based Manufacturing Applications	**3**
R	**Requirement for Better Fuel Efficiency**	Aircraft fuel efficiency, driven by environmental AND commercial imperatives; Automotive fuel efficiency	Short	STEEPLE	**3**
S	**Social Changes**	Ageing population; Social mobility	Medium	STEEPLE	**3**
T	**Skills and Labour Requirements**	Asian up-skilling = greater competition @ system level; Shortage laser process Engineers/ awareness; Alternatives to low cost off-shoring due to rising cost of labour in China = automation?;	Medium	STEEPLE	**3**
U	**Improved Yield**	Improved component yield, 100% yield / productivity systems	Medium to Long	Other	**2**
V	**High precision manufacturing**	High value, high precision medical components; Processing increasingly small components with tight tolerances.	Short	Industry Needs for Future Laser-based Manufacturing Applications	**2**
	Control		Medium	Other	**1**
	Big Data		Short	Other	**1**

3.3 Prioritisation of Laser-based Manufacturing Application Areas

Prioritisation Criteria

Each laser-based manufacturing application was assessed using two different and roughly separate considerations, namely Opportunity and Feasibility. *Opportunity* was defined as the magnitude of the opportunity that is plausibly available to an organisation; while *Feasibility* was defined as how well-prepared an organisation is to grasp the opportunity.

For both Opportunity and Feasibility criteria, a list of factors had been provided to all participants in advance of the workshop (Homework Slides 2 and 3 in Figure 2 and Figure 3), and each participant independently selected those he /she considered to be the most appropriate for assessing the manufacturing applications. All received votes were consolidated in advance of the workshop, and the total number of votes received for each factor is shown in Figure 5. The four top-ranked Opportunity factors and the three top-ranked Feasibility factors were identified used during the rest of the workshop. These are shown in Figure 6.

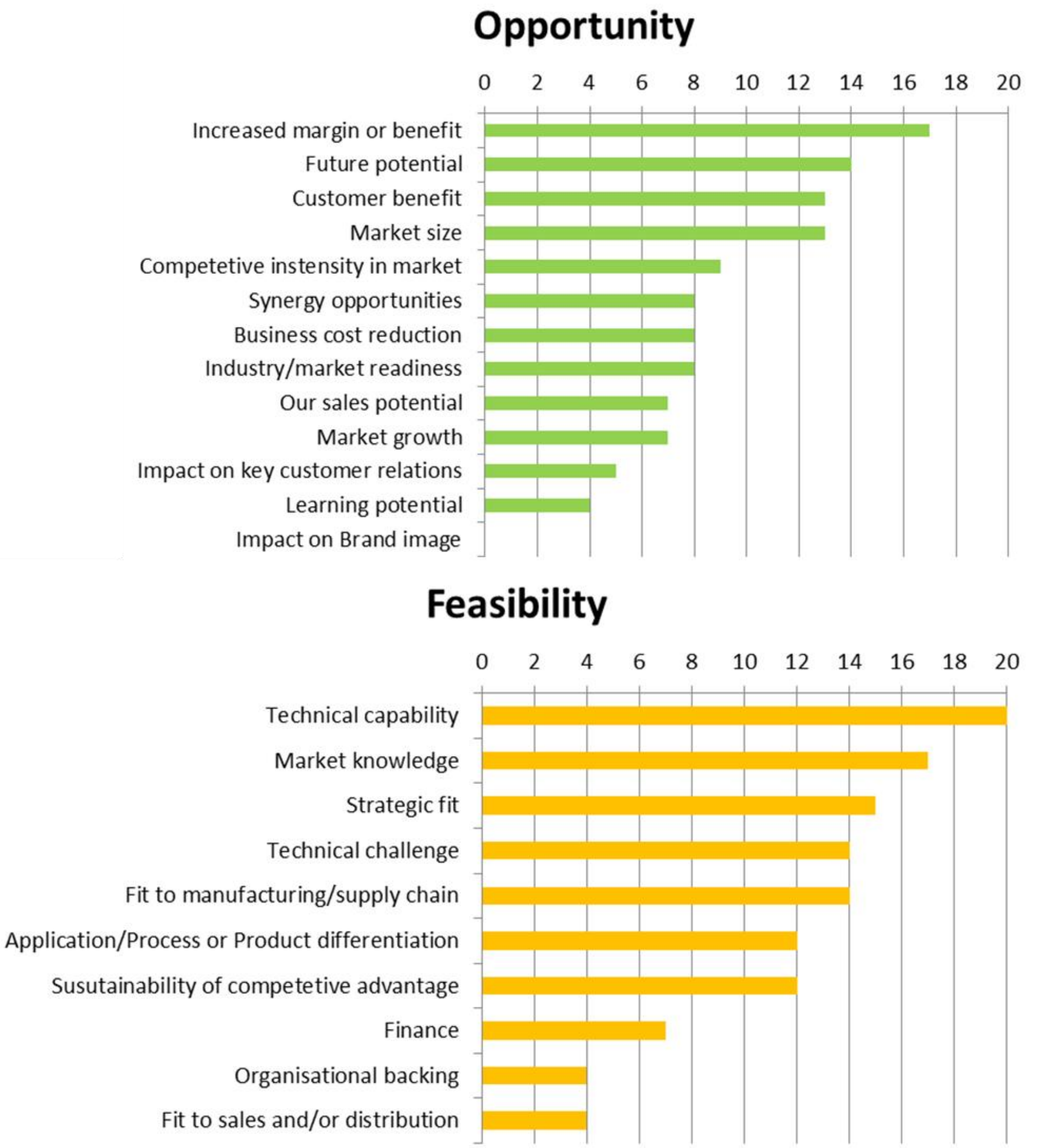


Figure 5: Total votes received for all the Opportunity factors and all the Feasibility factors.

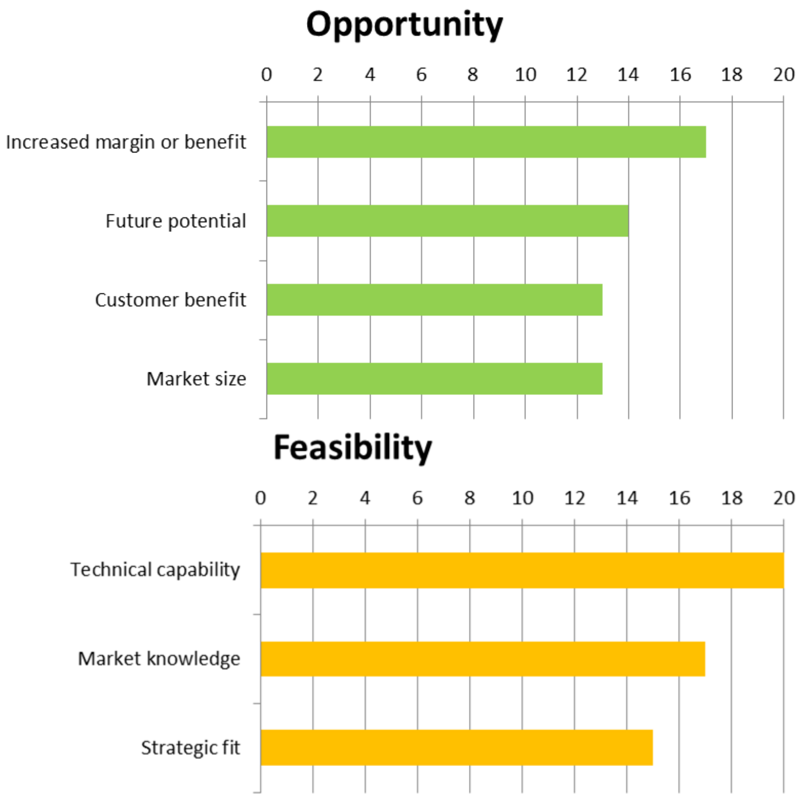


Figure 6: The top four Opportunity factors and the Top three Feasibility factors selected and used in the workshop.

Prioritisation Chart

A modified criteria-assessment process that involved *two* steps took place during the actual Workshop.

In the *first step* of this revised process *(Opportunity Factors)*, each participant was asked to review the consolidated list of 51 listed Manufacturing Applications and to use the four top-ranked Opportunity factors (see Figure 6) to select independently between 4-8 choices from the Manufacturing Applications list. Participants were discouraged from voting for the Applications they had contributed unless they were part of consolidated group or cluster.

In the *second step*, participants were asked to consider only applications that had already been selected using the Opportunity Factors, and for each of those selected to independently select from 4-8 Manufacturing Applications based on the three top-ranked Feasibility factors (see Figure 6).

By this process, a shorter list of 24 laser-based manufacturing applications was derived, to be considered further later during the Workshop. This shorter list contained a good balance between short and medium term applications but most fell into the ***new laser-based manufacturing techniques*** required for ***new engineering materials*** and ***material combinations*** layer of the roadmap. This short grouped list of selected applications of applications is shown in the chart in Figure 7.

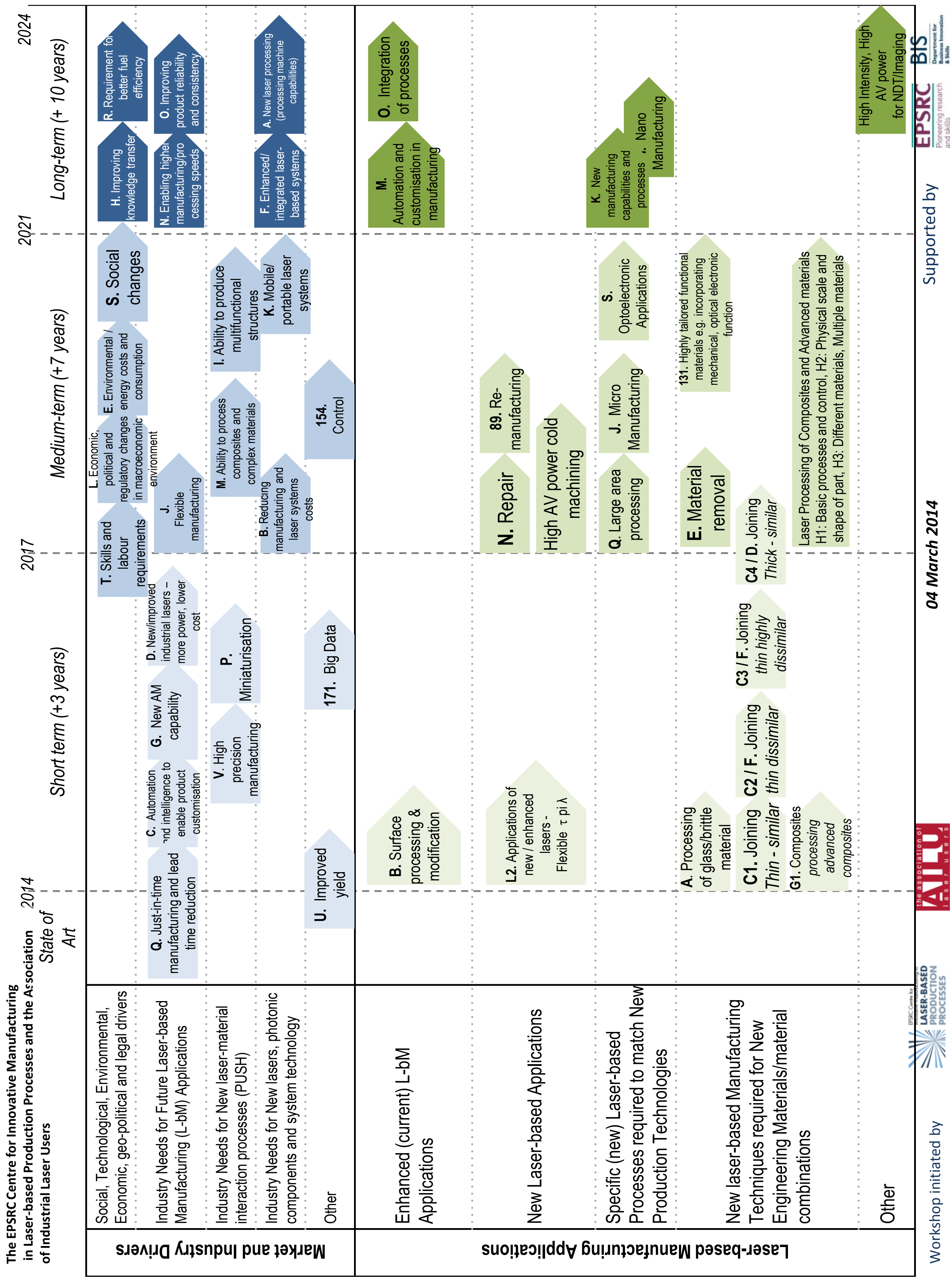


Figure 7: UK Roadmap Showing Prioritised Laser-Based Manufacturing Application Areas

This reduced list was subsequently transferred onto a 2x2 matrix with Opportunity shown on the vertical axis and Feasibility on the horizontal axis (see Figure 8 for an indication of the process). The objective here was to *facilitate decision making* and selection of the most appropriate applications to explore in much greater depth during the second main phase of the Workshop.

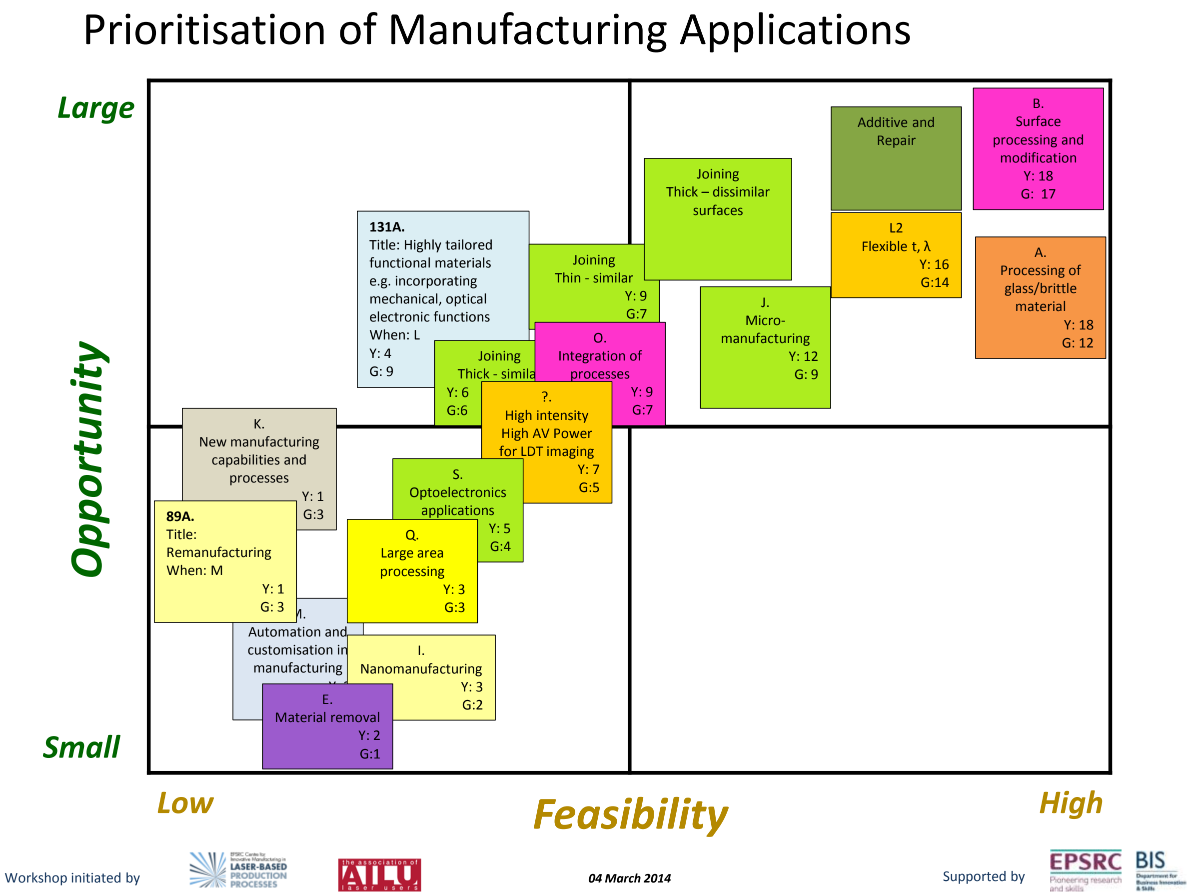


Figure 8: Indication of how the 2x2 matrix of Feasibility and Opportunity was used during the Workshop.

Applications placed on the top right quadrant (High Feasibility and High Opportunity) were of immediate interest, while Applications on the bottom right quadrant (High Feasibility and Medium / Low Opportunity) may represent suitable more long-term opportunities. Applications placed on the bottom left quadrant (Low Feasibility and Low Opportunity) were not automatically dismissed since it is possible they might be 'enablers' for other applications or in support of longer term prospects.

Final 'Manufacturing Application Area' Short List Selection

Six Workshop participants were nominated by the Workshop sponsors (AILU and CIM-LbPP) to make a selection of applications (or groups of applications that could be assessed together) they considered most appropriate to take forward for more detailed investigation by expert groups of the Workshop participants. Four applications were selected using a consensus process that took into consideration the following aspects to achieve a balanced selection:

- relative scores of each application and their position onto the 2x2 chart
- the timeline of the application (short, medium or long term)
- applications positioned most of the sub-layers of the roadmap
- the specific expertise of the Workshop participants

The four Application Areas selected for further exploration were:

1. **Additive Manufacturing (AM) including Repair**
   This included netshape and post processing, faster redesign of many components especially for aerospace applications, laser sintering, manufacturing of multi-materials and high speed powder bed fusion AM using combined laser and e-beam build processes.

2. **Joining materials including both thin and thick, similar and dissimilar materials**
   This included welding as a joining process, welding of lightweight structures, ability to weld ultra-high strength steel (UHSS), bonding of dissimilar materials e.g. glass-to-glass, glass-to-composites and sintering of crystalline powders into ceramics, adhesive-free bonding to eliminate contamination and stress-free optical bonding for beam and image transmission.

3. **Surface processing and modifications**
   This included laser texturing thin flexible glass for example to enhance the out-coupling for OLED lighting applications, laser cleaning/ablation technology, and general surface processing and modification applications.

4. **Micro-manufacturing**
   This included micro welding for medical and other applications, cutting of micro tubular components, microfluidics, micro-processing, parts assembly and placement, annealing and marking.

4.0 Deeper Exploration of Four Short-listed Application Areas

The Workshop participants were divided into four numerically roughly equal Groups based on individual background experience and declared interests, with each Group agreeing to explore one of the four Application areas in more depth. The distribution of Workshop attendees in each group was as indicated in **Appendix D**.

It was recognised at the outset that each of the four selected laser technology application areas can potentially address a broad range of manufacturing markets, including medical, aerospace, automotive, white goods, yellow goods, construction, defence, energy (oil and gas, renewables, nuclear), micro/macro electronics in displays, touch screens, sensors, MEMS and transport.

4.1 Generation of Specific Roadmaps for Short-listed Manufacturing Application Areas

The methodology used was for each of the four Groups to explore their Application Area using the following four sequential steps:

Step 1 The scope and boundaries of each application area was considered as well its long-term goal and vision.

Step 2 The links of each Application Area to the market drivers and needs were assessed;

Step 3 The groups then considered the technical feasibility especially in terms of the required system hardware, any success factors, knowledge gaps and the performance milestones that need to be put in place to implement the final vision.

Step 4 Finally, the key Research & Development priorities were summarised.

To assist the collaboration in working through these steps, each Group worked through the template shown in Figure 9 as a guide to the process. To facilitate these collaborations, each Group was issued with a very large poster version of Figure 9 to enable all members of each Group to ‘see the action’ and contribute to the creation of the embryo Roadmap for that topic. The documented outcome of these four intense parallel sessions was a completed version of Figure 9 (on a large Poster) for each of the four Manufacturing Application Areas.

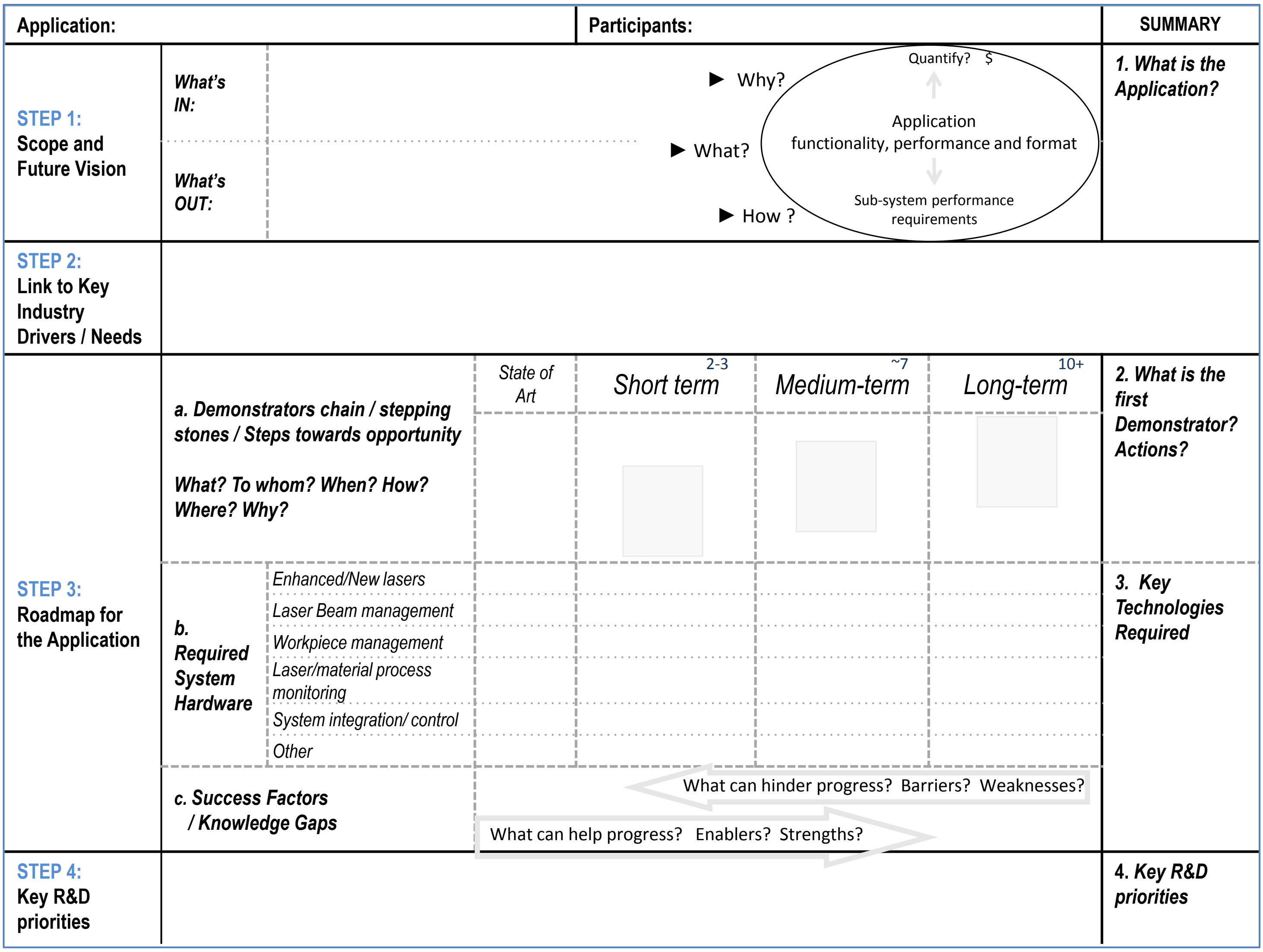


Figure 9: Blank Work-Book Template Used to Generate Roadmap for Short-Listed Application Areas.

The completed posters for each of the four Manufacturing Application Areas were transcribed by the *IfM* team in the days following the Workshop, and the FOUR e-versions (one for each Application Area) are shown in Figure 10, Figure 12, Figure 14 and Figure 16.

Using the content of the E-versions of Completed Roadmap poster templates as inputs, the IfM team generated the four high-level Roadmaps specific to each of the short-listed Manufacturing Application Areas.

Each of these Roadmaps includes:

- a more detailed specification for the application,
- the long-term vision for the application with the desired future performance characteristics,
- the milestones necessary to achieve the vision,
- specific system hardware requirements for each milestone and desired initial actions.

These are shown in Figure 11, Figure 13, Figure 15 and Figure 17.

Application: Additive Manufacturing | **Participants: CGR, JS, AW, MG, LS** | **SUMMARY**

STEP 1: Scope and Future Vision

Low→Median Volume

		Why? / What? / How?	
What's IN:	High added value. Basic processes and control. Laser sources; process control, application of lasers. Different materials, multiple materials. Repair. Physical scale and shape of part. Sensing and control of process →brown powder	▶ Why? Diode, Solid state. Lasers	Industrialised applications; 100s to 1000s (low) per annum
What's OUT:	Low value home/consumer 3D printing. Functional grading materials. E-beam. Cladding.	▶ What? Accuracy – normal manufacturing tolerances; ▶ How ?	£Billion machines; Smaller proportion for laser source value

1. What is the Application? Medical, Aero, Military, Automotive. Prototype/Rig parts → towards full parts. Custom parts personalised

STEP 2: Link to Key Industry Drivers / Needs

C-Automation and intelligence for customisable product. E-Cost and consumption. J-Flexible manufacture. Design freedom.

STEP 3: Roadmap for the Application

Distortion free. Favourable micro structure. Favourable residual stresses. Produce fully dense part.

a. Demonstrators chain / stepping stones / Steps towards opportunity

What? To whom? When? How? Where? Why?

(PB) Powder bed.

Repair; -BP, -Wire

(BP) Blown powder.

	State of Art	Short term 2-3	Medium-term ~7	Long-term 10+
a. Demonstrators	Near net shape → net shape (both)	Process control (both). Managing residual stress (BP)	Fully dense part with correct microstructure (both).	No post process → finished prod (both)

b. Required System Hardware

	State of Art	Short term 2-3	Medium-term ~7	Long-term 10+
Enhanced/New lasers	300-500 w laser (fibre)	Laser peening – new sources		
Laser Beam management				
Workpiece management	Limit size 500 x 500 x 500 max workpiece.	Automatic load/unload	Adaptive optics – modifying beam profiles	In situ repair. Closed loop process.
Laser/material process monitoring				
System integration/ control	No process control	Programming and simulation to allow adaptive optics	Multiple beams? Multiple lasers? – Control/calibration	
Other				

c. Success Factors / Knowledge Gaps

BP software and local manufacture lacking. Laser literacy; -engineers, 'designers. Process capability. Understanding process capability – engineers. Powder supply chain – risk.

Strength – lasers (solid state). Research (Unis); sensors, -optics, -modelling + simulation.

2. What is the first? Fully dense parts. BP distortion free bar demonstrator. Multi axis complex share. Shot peening without shockwave fluid etc. Link to AM national strategy & photonics 21 +H2020. Maximum spot size maintaining output characteristics. PB surface finish for fatigue parts.

3. Key Technologies Required Scanning. Sophisticated. Adaptive optics. Beam delivery + control → precision + speed.

STEP 4: Key R&D priorities

Distortion control. Understanding heat profiles. Titanium inco graded material. Microstructure + residual stress. Laser material interaction understanding → powder. Process output monitoring and analysis. Can process control for laser process to other processes? System integrators. Encourage UK supply chain (AM). Missing machine/tool integrators.

4. Key R&D priorities Laser power not an issue. Beam delivery is.

Figure 10: E-version of Completed Roadmap template for Additive Manufacturing including Repair

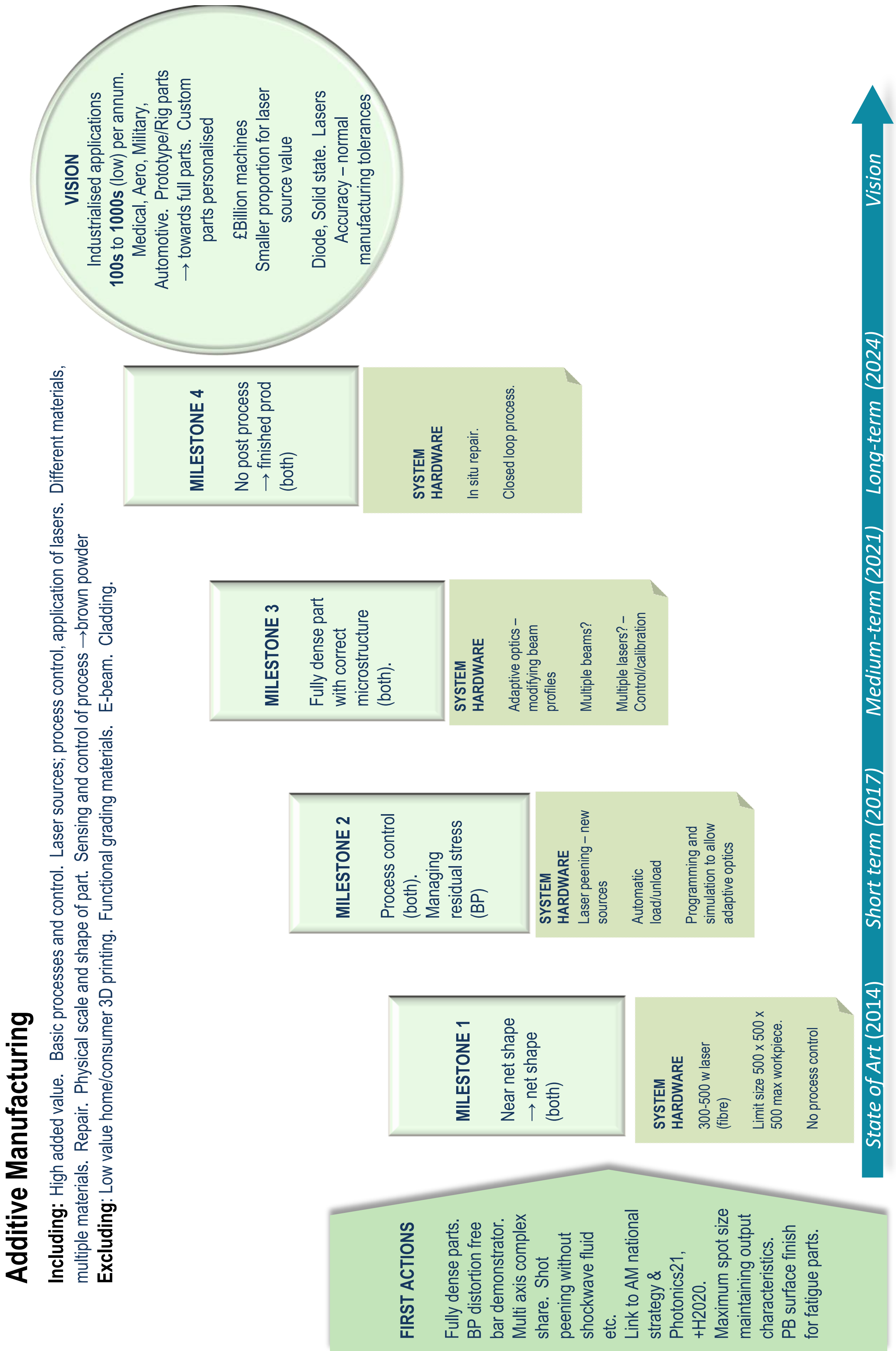


Figure 11: Consolidated Roadmap for Additive Manufacturing including Repair

Application: Joining thin dissimilar materials

Participants: Robert Lamb, Neil Mair, Paul Hilton, Stewart Williams, Nick Langfield, Simon Fung (?)

SUMMARY

STEP 1: Scope and Future Vision

Low→Median Volume

What's IN: Any thickness including similar and dissimilar laser hybrid systems. Engineering application; medical, white goods, yellow goods, construction, defence, energy (oil + gas renewables, nuclear), transport.

What's OUT: Additive manufacturing

▶ Why? ▶ What? ▶ How ?

1. Good quality. As good as art welding
2. Cost no more than 2 times that of art welding
3. Expert systems for laser control
4. Joins for functionality other than strength e.g. Light weighting

1. What is the Application?

STEP 2: Link to Key Industry Drivers / Needs

D is the driver for (1). B&D drivers for (2). J driver for (2). N driver for (2). B&D are the same. E is the driver for (3). C is driver for (3). A is one of drivers for (3). Eliminating T driver for (3). H driver for (3). R driver for (4). E driver for (4). M driver for (4).

STEP 3: Roadmap for the Application

Automotive
White goods
Defence
Transport
EARLY

		State of Art	Short term	Medium-term	Long-term
a. Demonstrators chain / stepping stones / Steps towards opportunity *What? To whom? When? How? Where? Why?*		Expert operated, expensive and bespoke – expert. Expert system (4). Material science (1). Element of welding (4). Dissimilar materials (3)	Bond a piece of glass to metal and check for corrosion etc. Optical quality (1). Expert – self programming smart laser (4), (1), (3). High power at different wavelengths impact on quality – tailor wave lengths (2). De-mystifying the laser welding process. Improve the processes to deliver higher and consistent quality eg hybrid lasers (1).	Process monitoring expert system (4), (1), (3). Online inspection of internal defects. Cheaper lasers over time as coming down (2).	Expensive – don't make enough – too much R&D! (2). Dynamic control of laser welding process (4), (1), (3). Fully automated (4) – gauge the extent of requirement automatically. Self assessment on faults/issues (3)
b. Required System Hardware	*Enhanced/New lasers* *Laser Beam management* *Workpiece management* *Laser/material process monitoring* *System integration/ control* *Other*	Good models that can work on PC especially distortion. Better assumptions and more efficient models.	Use of tailored energy distributions for dissimilar joining. Depth of focus control. Beamwaist. Control of focus position. Micro precisioning positioning. Penetration control. Keyhole stability.	Laser cost – key enhancement ownership and manufacturing cost. Porosity control. Spatter and undercut detection and over penetration => integration into control loop. Well-quality control. Weld shielding (understand and control). Process control gas flexible clamping systems. Distortion control and predictions. Tooling and the right/standard way of doing. Diode laser 800. Shorter wavelength to avoid plasma plume, better absorption.	Multi kilowatt wavelength – different available to meet needs. Different materials.
c. Success Factors / Knowledge Gaps		Get rid of black art – more fundamental science!!! In collaboration with engineers. Approach the problem in a new way – not point and shoot. Engineering standards to control the process (lack of)		Good beam analysis systems > reliable optics, better lasers > stable lasers. Making progress on monitoring systems.	

2. What is the first Demonstrator? Actions?
Developing expert systems to control a process and improve quality of laser joining.

3. Key Technologies Required
Process monitoring systems – fast response systems with data processing. Low cost lasers!

STEP 4: Key R&D priorities

Process monitoring and control.

1. Expert system develop
2. Distortion/process modelling
3. Fundamental science of joining
4. Gas shielding understand
5. Gases
6. Porosity control
7. Material science of dissimilar materials

Improved consumables for laser welding. Interpretation of cons with weld pools.

4. Key R&D priorities
Full process control. Elimination of the Black Art.

Figure 12 E-version of Completed Roadmap template for Joining dissimilar materials.

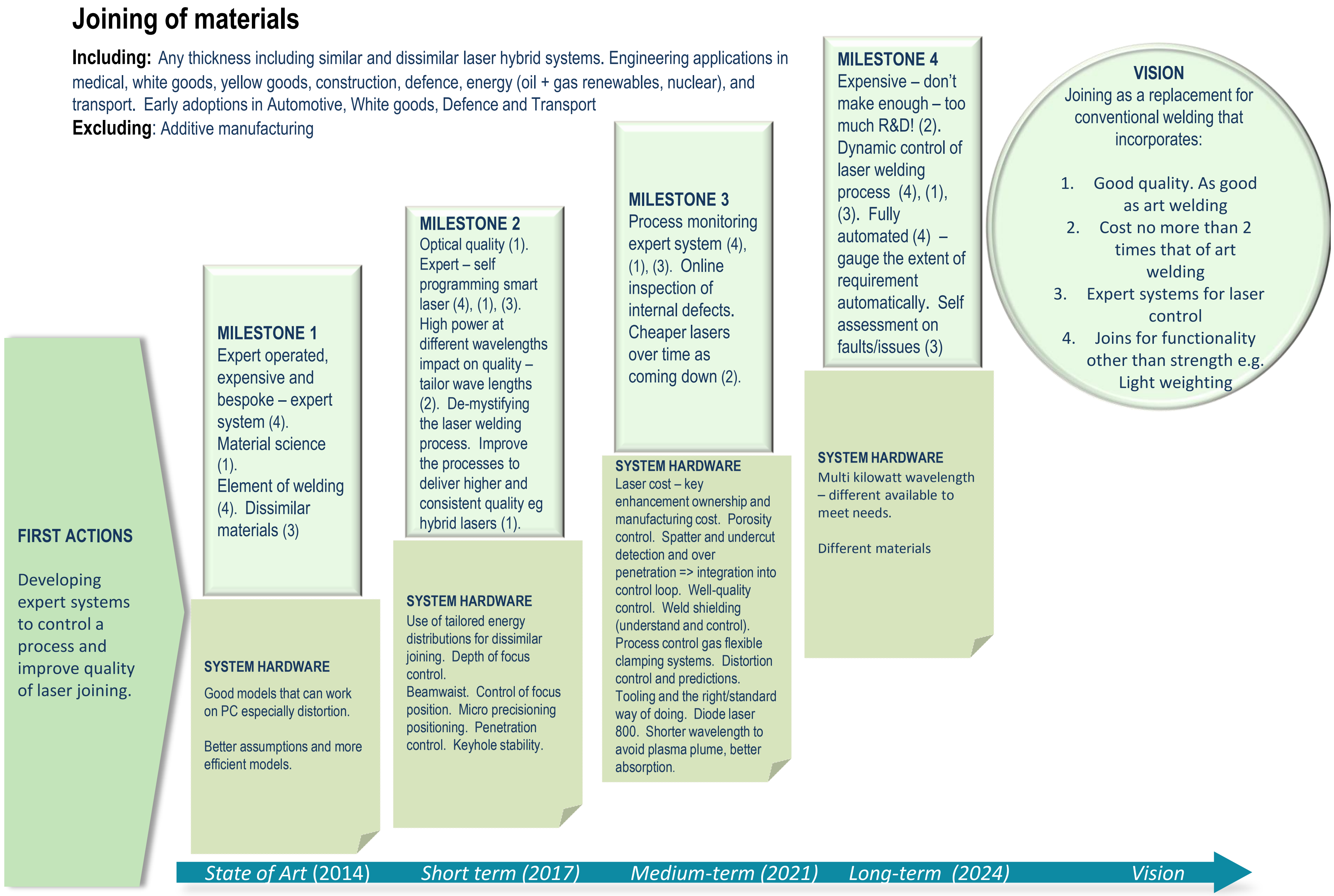


Figure 13: Consolidated Roadmap for Joining dissimilar materials.

Application: Surface processing and mods
Overlap with Micro machining

Participants: Ric Allot, Mark Godssens, Adam Brunton, Mike Green, Duncan Hand, Roy McBride, Karen Brakspear.

SUMMARY

Low→Median Volume

STEP 1: Scope and Future Vision

What's IN: Peening. Make surface stronger/smoother/Bioinspired/ rougher. Added functionality - ↑↓ resistance. Friction. Controlled scattering (reflective surfaces). Heat treatment (already well developed). Annealing; -Amorphous silicon, - Solar.

What's OUT: Laser marking. Lenticular arrays. Aesthetics. 10mm depth limit.

▶ Why? 1 sec/diagonal inch. $20Bn. 100mm res.
▶ What? Quantify? $ · Application functionality, performance and format
▶ How ? Sub-system performance requirements

1. What is the Application? Cell/tissue – material interaction in medical devices. ↓ air/water resistance Hydrophilic/Hydrophobic – microfluidics Mechanical strengthening. Lighting/displays

STEP 2: Link to Key Industry Drivers / Needs

- Cost/M² (↓ system costs), ↓ manufacturing costs.
- New laser processing capabilities
- Improve environmental impact/energy usage. (↓chemical usage)
- Component lifetime enhancement.
- Improve product reliability

STEP 3: Roadmap for the Application

a. Demonstrators chain / stepping stones / Steps towards opportunity

What? To whom? When? How? Where? Why?

State of Art	*Short term 1-2 years*	*Medium-term 5 years*	*Long-term 10 years*
•High prf 1kw fs laser. •High speed galvo scanners. •High speed polygonal. •Chemical/ mechanical processes laser polishing	•CM² compatibility •Identify contacts/stakeholders /key opinion leader •Develop process with current laser SoA. Compare to other competing techniques.	•M² capability but ↑ cost. •Reduce costs of (laser) process. •Develop to "real" 3D/2D systems	•M² capability but ↓ cost high throughput. •Highly reliable system

2. What is the first Demonstrator? Actions? •Large area modification, eg 10 cm². •Where surface functionality is added.

b. Required System Hardware

	State of Art	*Short term 1-2 years*	*Medium-term 5 years*	*Long-term 10 years*
Enhanced/New lasers	•High PRF fs laser.	Optimised short pulse lasers (power/reliability). High power UV lasers.		
Laser Beam management		•Improved beam shaping/capability.	•3D multiaxial	
Workpiece management	•High speed galvo & polygon scanner	•Dynamic parallel processing •High speed	•Materials processing •Real time sensing	
Laser/material process monitoring		•Synchronisation of scanners/stages for 2D.	High speed synchronisation of scanners & stages for complex 3D	•Sensors for 3D workpiece
System integration/ control		•Surface profile imaging (integrating current technology		•Real time feedback control
Other				

3. Key Technologies Required •Integration/synchronisation •Beam control •Real-time (10x faster) sensor control •Robust/cheaper/24/7 capable/ultrafast lasers.

c. Success Factors / Knowledge Gaps

What can hinder progress? Barriers? Weaknesses? — Lack of focus – behind competitors

What can help progress? Enablers? Strengths? — Good underlying R&D capabilities. Market is there (as is supply chain).

STEP 4: Key R&D priorities

- Better ultra fast lasers (or what kind of lasers are needed?) – Reliability.
- Processing of multiple materials.
- Process development.
- Monitoring and control systems.
- Synchronisation/parallel processing.

4. Key R&D priorities

Figure 14: E-version of Completed Roadmap template for Surface processing and modifications

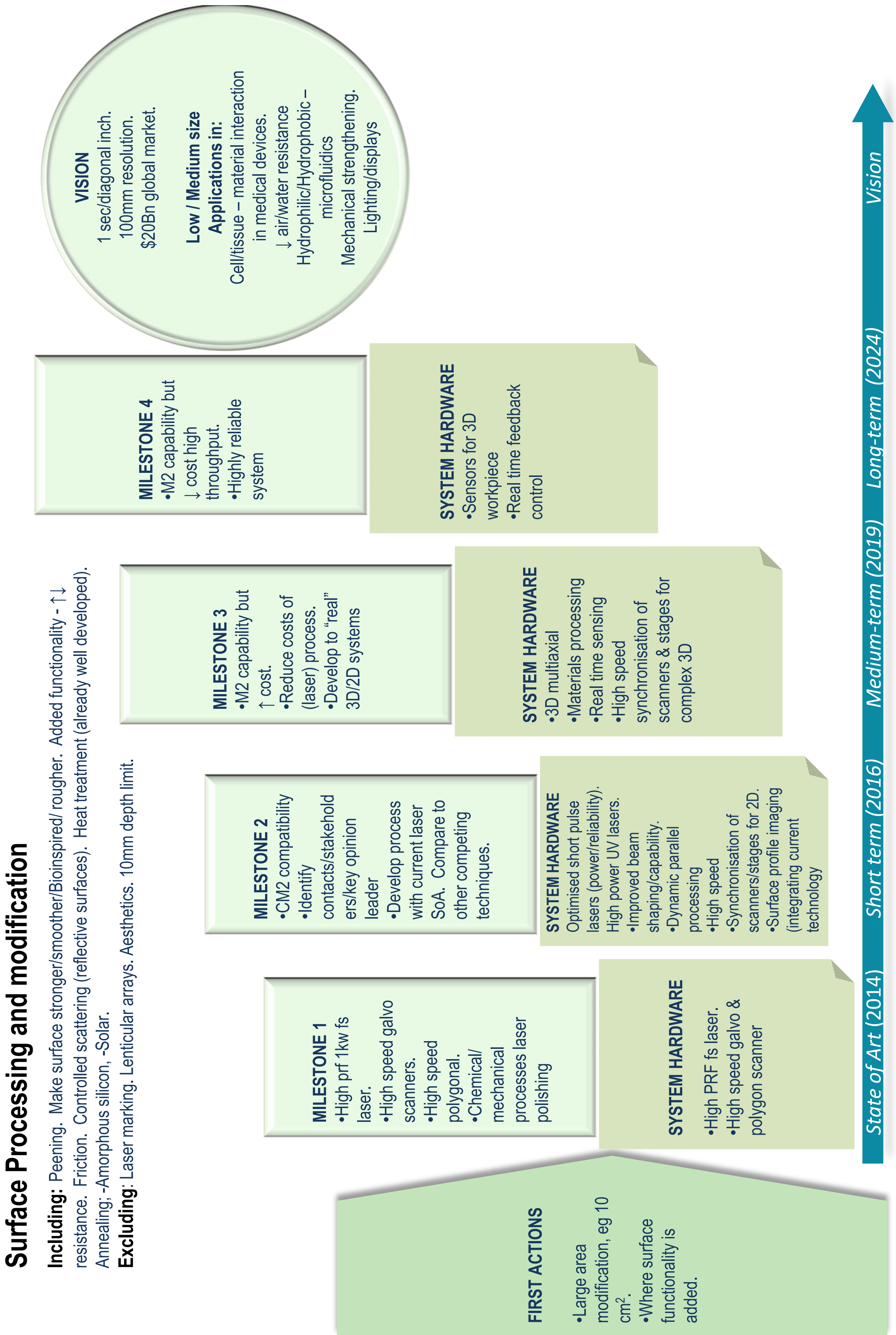


Figure 15: Consolidated Roadmap for Surface processing and modifications

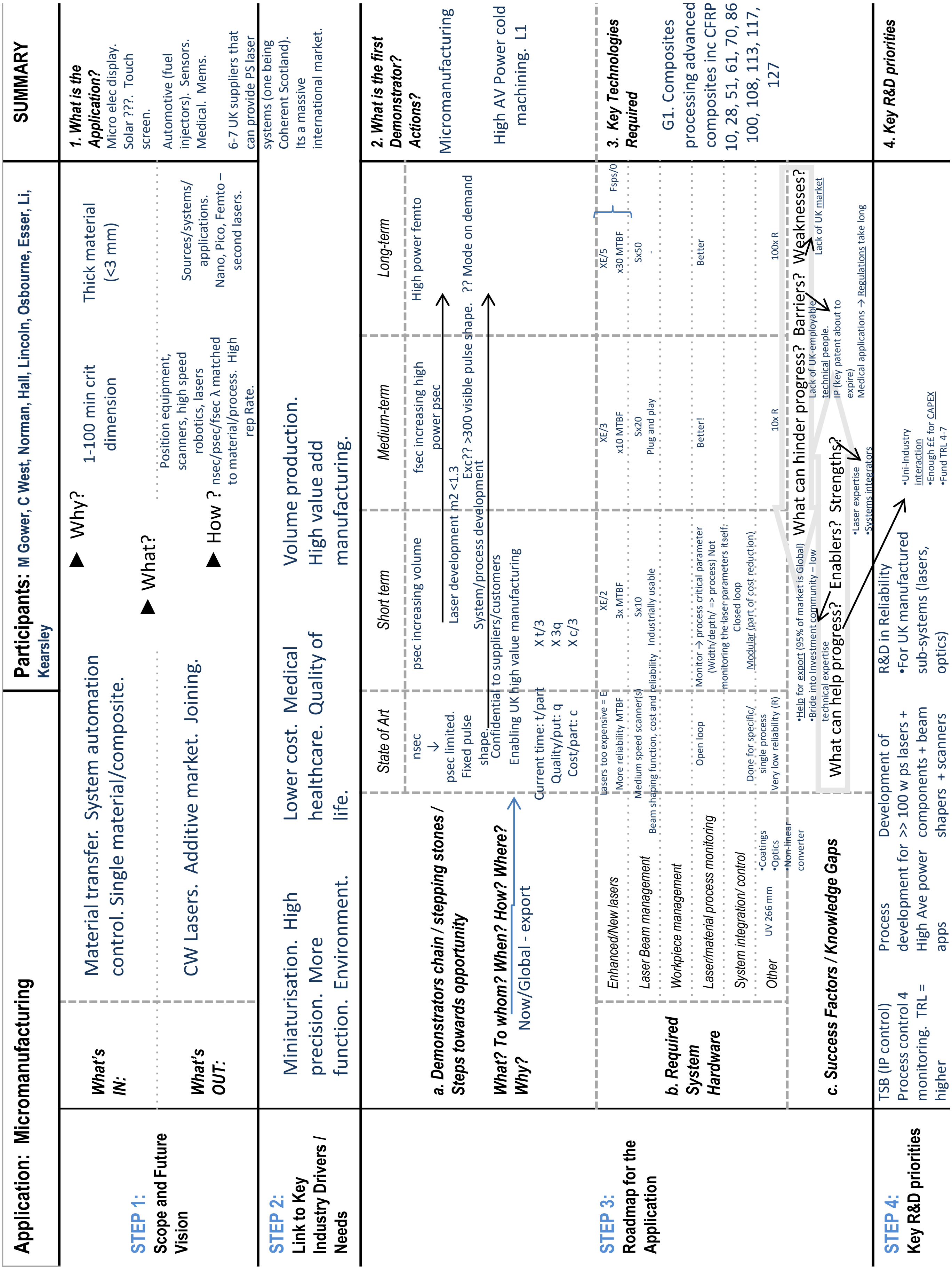


Figure 16: E-version of Completed Roadmap template for Micro-manufacturing.

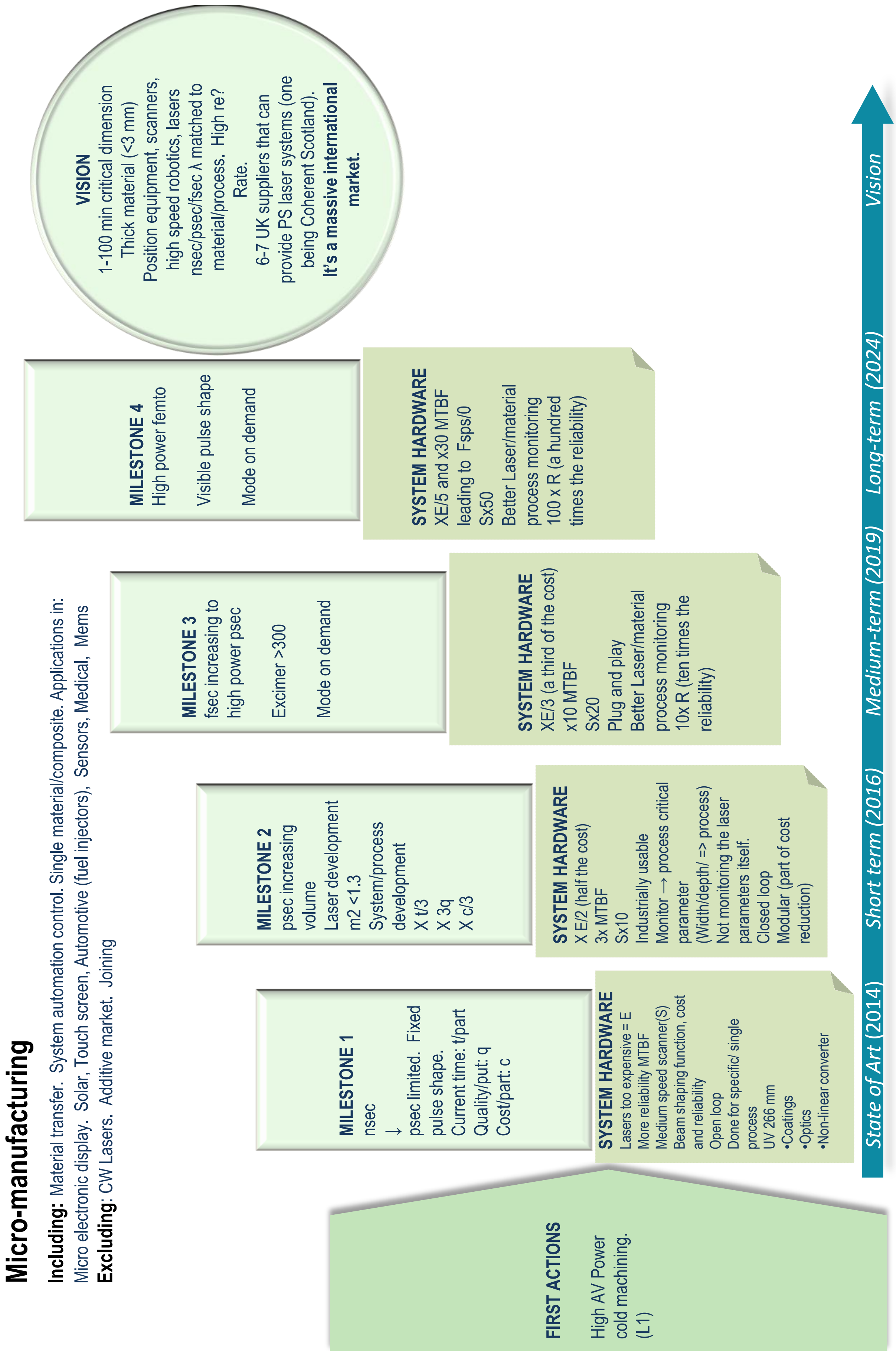


Figure 17: Consolidated Roadmap for Micro-manufacturing.

4.2 Links of Shortlisted Application Areas to Market Drivers

When considered collectively, the four Application areas link well to each of the top five market needs and drivers and reasonably well to all the rest. It is perhaps particularly noteworthy that "Enhanced/ Integrated laser-based systems" was earlier in the day rated as being among the top ten most powerful market and industry needs. Its importance is perhaps also reflected in the identified **research and development priorities**, discussed in the next section, which will address this market driver.

The links of the selected Application Areas to the market needs and drivers are shown in Table 2.

Table 2: Links of the market drivers & needs to the selected laser-based manufacturing Application Areas.

			APPLICATION AREA			
			Additive Manufacturing including Repair	Joining materials	Surface processing and modifications	Micro-manufacturing
MARKET DRIVERS AND NEEDS	A	New Laser Processing / Processing Machine Capabilities		■	■	
	B	Reducing Manufacturing and Laser System Costs		■	■	■
	C	Automation and Intelligence to Enable Product Customisation	■	■		
	D	New / Improved Industrial Lasers - More power, lower cost		■	■	
	E	Environmental / Energy Costs & Consumption	■	■	■	■
	F	Enhanced / Integrated Laser-based Systems	■	■	■	■
	G	New AM capability	■			
	H	Improving Knowledge Transfer		■		
	I	Ability to produce Multifunctional structures				■
	J	Flexible Manufacturing	■	■		
	K	Mobile / Portable Laser Systems				
	L	Economic, Political & Regulatory Changes in Macroeconomic Environment				
	M	Ability to process Composites & Complex Materials		■		
	N	Enabling higher manufacturing / processing speeds		■		
	O	Improving Product Reliability & Consistency			■	
	P	Miniaturisation				■
	Q	Just in Time Manufacturing & Lead time Improvement				
	R	Requirement for Better Fuel Efficiency		■		
	S	Social Changes				■
	T	Skills and Labour Requirements		■		
	U	Improved Yield				
	V	High precision manufacturing				■

5.0 Technologies and Required R&D Priorities

5.1 Research and Development Priorities

The following technologies and R&D activities were deemed most important by the participants to support the development plans of the laser-based manufacturing applications as well as strengthen the UK research capability as a whole:

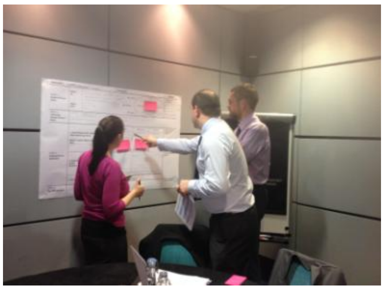
- Improve the fundamental understanding of laser-material interaction and eliminate the "black art" currently associated with laser-based manufacturing processes. In particular, understanding and controlling material and / or join distortion, heat profiles, gas shielding, microstructure and residual stress for a range of materials were regarded as very important. Furthermore, research in material science of dissimilar or advance materials was also considered a critical long term goal.
- Process output monitoring, analysis and control were regarded as of key importance in this field. This incorporates process modelling, porosity control, process development for high average power applications, processing of multiple materials as well as process synchronisation and / or parallel processing. Ultimately, full integration of different laser processes and subsequent integration of laser processes with other manufacturing processes is required to advance this area. This needs to incorporate sensors to enable the development of faster response systems by a factor of 10 or more with the ability of real-time data processing and control.
- Better or new lasers and laser systems are required for the new manufacturing processes and applications. This includes, faster (picosecond and femtosecond), higher power, lower cost, more reliable lasers capable of continuous operation. Integration of lasers into machines, tools and equipment is also required and this needs to be supported by an improvement of the quality and availability of laser consumables.
- Beam delivery and control is currently an issue for many laser-based manufacturing processes. Beam shaping can inadvertently affect precision and speed. Better beam characterisation, diagnostics and manipulation, possibly with the inclusion of adaptive optics are necessary to allow wider use of lasers in manufacturing.
- Development of sophisticated, high speed scanners and scanning systems is also a priority in the field.

Table 3 shows each of the R&D priorities that emerged from the workshop and their applicability/relevance to the four laser-based manufacturing applications.

Table 3: Relevance of R&D priorities to Short listed Application Areas

		Laser-based Manufacturing Application Areas			
		Additive manufacturing	Joining materials	Micro-manufacturing	Surface processing
Key Research Priorities	Process monitor control	x	x	x	x
	High power short wavelength lasers	x	x	x	x
	Sensors and control	x	x	x	x
	Beam characterisation & diagnostics. Beam manipulation, beam shaping.	x	x	x	x
	Key need for very high speed scanners and control of scanners. Creation of scanning systems for m-features.	x		x	x
	Close loop system	x	x		
	Materials science understanding and fundamental science of welding especially around material melting dynamics.	x	x		
	Eliminations of black art				
	Modelling	x	x		
	Expert systems	x	x		
	Shielding system (BP).	x	x		
	Laser peening	x			x
	Laser polishing – for improving surface of additive manufacturing parts.	x			x
	Development of lower cost lasers for processing and surfacing. Reliable low cost ps fs lasers.			x	x

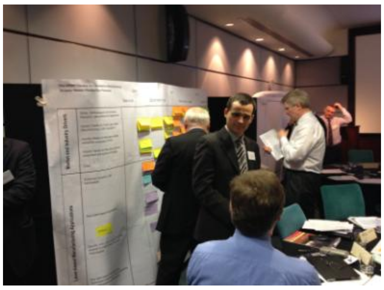
5.2 Strengths, Weaknesses, Knowledge Gaps and Enablers



The main strengths and weaknesses as well as the knowledge gaps of the UK laser sector were captured during the workshop. The UK appears to be strong in solid state and fibre laser technologies, with highly-rated academic laser research and expanding commercial laser companies. The UK is also strong in other research activities that are required to develop the new generation lasers and laser systems such as optics, modelling and simulation, sensors, analysis and monitoring systems.

There is good international market demand for lasers and a well-established supply chain in the industry of component manufacturers, laser system integrators and laser users who can continue to support current and future developments in this sector.

The weaknesses identified were mainly around shortage of engineers with some certain technical and engineering skills required for the next generation of lasers and materials processing, including areas related to system integration. Inadequate capability and knowledge related to laser manufacturing process improvement was also raised as an issue. The low UK market take-up/demand for laser-based systems in manufacturing (e.g. compared to Germany) which is evident across diverse areas of UK industrial engineering appears to indicate a low level of appreciation of the commercial benefits of these technologies. Also, the weak position of UK industry in the supply chain for powders required for innovation in additive manufacturing was identified as a risk. Finally, laborious and time consuming regulations in the medical sector were also seen as a weakness to properly exploit lasers and laser technology in this large sector.



Key knowledge gaps mentioned included suitable beam analysis technology to enable the development of improved beam delivery and control in manufacturing processes. Understanding in detail the process capability and laser-material interactions is also seen as very important and one of the key research priorities identified in the previous section. New approaches and innovations are required to progress this area with stronger collaborations and links both with the academic community and industry engineers. Better engineering standards need to be established to allow tighter control of laser-based manufacturing processes.

Finally, the 'enablers' discussed were predominantly around economic support or incentives i.e. help on exporting since 95% of the market demand is outside the UK, availability of investment especially for capital equipment and better public funding for application and demonstration projects (Technology Readiness Levels 4-7). Finally better knowledge transfer between industrialists, academics and engineers was seen as important in speeding up progress in this field.

Table 4 summarises the UK strengths and weaknesses, knowledge gaps and potential enablers, as derived from the Workshop process.

Table 4: Strengths Weaknesses, Knowledge Gaps and potential enablers for UK laser-based Manufacturing

UK Strengths	UK Weaknesses
• Solid state and fibre laser technologies. • Research on optics, modelling and simulation, sensors and analysis and monitoring systems. • Good international market demand for lasers and laser systems. • Well-established supply chain in the laser industry of component manufacturers, laser system integrators and laser users.	• Shortage of relevant technical and engineering skills required for the next generation of lasers and materials processing, especially around system integration. • Low capability and knowledge on process improvement. • Very small UK market demand for lasers and laser systems. • UK position in the powder supply chain. • Heavy regulations in the medical sector. • UK innovation lacking behind this of other countries.

Knowledge Gaps
• Beam profiling software to enable the development of improved beam delivery and control in manufacturing processes. • Detailed understanding of process capability and laser-material interactions. • *“Thinking outside the box”* approaches to speed up innovations in the sector. • Designing and establishing engineering standards to achieve better control of laser-based manufacturing processes.

Enablers
• Economic support or incentives i.e. exporting, finance for capital equipment and public funding for application and demonstration projects. • Collaboration and knowledge transfer between industrialists, academics and engineers.

6.0 Conclusions

A Roadmapping Workshop organised and sponsored by the Association of Industrial Laser Users and the EPSRC Centre of Innovative Manufacturing in Laser-based Production Processes was conducted in March 2014.

The workshop brought together 29 participants from UK industry, academia and the public sector to explore market and industry needs, prioritise relevant applications and assist in developing R&D priorities for the UK.

It was judged that laser systems can play an important role in meeting current and future market requirements across a range of areas including processing of advanced, dissimilar or brittle materials, reducing manufacturing costs, increasing manufacturing speeds and reducing environmental impact from industrial activity.

Four laser-based manufacturing processes were selected as priorities due to their potentially widespread impact on a range of different markets from medical and aerospace, to microelectronics and transport. These are:

- Additive Manufacturing, including Repair
- Joining materials including both thin and thick, similar and dissimilar materials
- Surface processing and modification
- Micro-manufacturing

In prioritising future R&D investment needs, there was recognition of the need for a more structured focus on achieving deeper, quantitative understanding of laser material interaction science as core underpinning for the realisation of more predictable and transferable laser-based manufacturing processes. The need exists for such an approach to embrace (but not exclusively) manufacturing applications of advanced, dissimilar and brittle materials. A further essential requirement is the development of improved laser-process monitoring techniques with reliable associated hardware that can be integrated into automated machines.

The continuing need for sustained R&D at all levels in the in the supply chain for laser-based production machines was also recognised. On the hardware component side, R&D is required that addresses both fundamental laser device technology and improved techniques and components for laser beam manipulation including high-speed, real-time (adaptive) control. In addition, there was frequent mention of the need to incorporate increased levels of automation in laser tools and machines, while reducing cost of ownership through increased productivity and reduced environmental impact.

7.0 Future Actions

The next step in the Roadmapping exercise is to distribute this Interim Report on the outcomes of the 1-Day Roadmapping Workshop to the broader UK Laser Materials Processing community to provide an additional round of consultation to help produce a more definitive UK Roadmap-2014 for Laser-based Manufacturing Applications.

The dissemination of this Interim Roadmapping Report is accompanied by a Consultation Template, which is aimed at facilitating the collection of a broader range of inputs from across our community on the key outcomes of the Workshop. As far as possible, opinions gathered in this way will be incorporated in a subsequent final UK Roadmap-2014 for Laser-based Manufacturing Applications. The aim is for this document to be completed and distributed in the late autumn of 2014.

8.0 References

[1] Farnham AILU Meeting Farnham Report 'First steps of a strategy for Laser Materials Processing in the UK: Report of the UK Laser Materials Processing Strategy Workshop Farnham Castle, Surrey 21 & 22 February 2012' Published by the Association of Laser Users (AILU) August 2012. http://www.ailu.org.uk/laser_technology/the_laser_user_magazine/articles/6722.html

[2] Main Photonics21 website at: http://www.photonics21.org/
Particularly see "Photonics Strategic Multiannual Roadmap" (April 2013), and outputs of:
- Work Group II, 'Industrial Manufacturing and Quality', pp35-41, and
- Work Group VI 'Design and Manufacture of Components and Systems' pp70-83

at: http://www.photonics21.org/download/Brochures/Photonics_Roadmap_final_lowres.pdf

[3] 'The Future of Manufacturing: An Era of Opportunity and Challenge for the UK' Foresight Report from the UK Government Office of Science, London (November 2013). Main report and summary documents.
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/255923/13-810-future-manufacturing-summary-report.pdf

[4] 'Factories of the Future - Multiannual roadmap for the contractual PPP under Horizon 2020' Prepared by European Factories of the Future Research Association – a MANUFACTURE initiative and Published by European Commission, Luxembourg: Publications Office of the European Union, 2013, ISBN 978-92-79-31238-0, doi:10.2777/29815.
http://www.effra.eu/attachments/article/129/Factories%20of%20the%20Future%202020%20Roadmap.pdf
See also:
http://www.effra.eu/index.php?option=com_content&view=category&layout=blog&id=85&Itemid=133

[5] 'Harnessing Light: Optical Science & Engineering for the 21st Century' US National Academies Press, 1998. http://www.nap.edu/catalog.php?record_id=5954

and

'Optics and Photonics: Essential Technologies for Our Nation' US National Academies Press, 2013. http://www.nap.edu/catalog.php?record_id=13491

[6] 'Report on the UK Roadmapping Workshop of Laser-based Manufacturing Applications 04 March 2014' Dr Nicky Athanassopoulou, IfM Education and Consultancy Services, Cambridge, 2014.

Appendix A: Workshop Attendee List

	NAME	ORGANISATION
INDUSTRY	Adam Brunton	M-Solv
	Simon Fung	AWE
	Simon Gardiner	Airbus
	Mark Greenwood	JK Lasers
	Mike Green	The Association of Industrial Laser Users
	Paul Goodwin	Laser Cladding Technology
	Malcolm Gower	Nanophoton Technologies
	Clive Grafton-Reed	Rolls Royce Ltd
	Denis Hall	Rofin-Sinar UK Ltd
	Paul Hilton	TWI
	Andrew Kearsley	Oxford Lasers
	Robert Lamb	Selex Galileo
	John Lincoln	Harlin/Photonics CIM
	Nick Longfield	Manufacturing Technology Centre
	Neil Main	Micrometric Limited
	Roy McBride	Power Photonic Ltd
	Steve Norman	SPI Lasers Ltd
	Mike Osborne	OpTek Systems
	Jagjit Siddhu	BAE Systems
	Craig West	Attica Components
ACADEMIA	Mark Goossens	Fraunhofer Centre for Applied Photonics
	Daniel Esser	Heriot-Watt University
	Duncan Hand	Heriot-Watt University
	Lin Li	University of Manchester
	Stewart Williams	Cranfield University
GOVERNMENT	Ric Allott	STFC
	Ian Williams	BIS
	Alastair Wilson	ESPKTN
FACILITATORS	Nikoletta Athanassopoulou	IfM ECS
	Karen Brakspear	EPSRC
	Veronica Ferguson	CfIM Laser-based Production Processes
	Louise Jones	ESPKTN
	John McManus	IfM ECS
	Alex Peden	CfIM Laser-based Production Processes

Appendix B: Guidance Notes for pre-Workshop Homework

UK Roadmapping Workshop

Laser-based Manufacturing Applications

Tuesday 04 March 2014

Workshop Facilitators: Dr Nicky Athanassopoulou (*Institute for Manufacturing, Cambridge University)*
Mr John McManus (*Institute for Manufacturing, Cambridge University)*

WORKSHOP AGENDA

09.45	Arrival – Coffee	
10.15	Welcome, Introduction and Overview	
10.30	Individual Presentations on Drivers, Applications	All
11.45	Prioritisation Criteria -	Dr Athanassopoulou
12.00	Prioritisation of most important Applications	All
12.30	Selection of top 5-8 Applications	All
13.00	***LUNCH***	
13.45	Break-out Group Work: Explore the selected applications	Groups
15.30	Identify/Understand the technologies to be developed/integrated	Groups
16.30	Feedback and Review	All
17.30	Close	

UK Roadmapping Workshop: Laser-Based Manufacturing Applications

Introduction

One of the main outcomes of the Workshop on Laser Materials Processing (LMP) held at Farnham Castle in February 2012 [2] was a widely-shared recognition of the need to produce a Roadmap (relating to both laser-based manufacturing applications and required hardware), which is relevant to UK researchers, manufacturing-user and technology-supply companies, as well as providing an evidence-base for strategic planners and UK funding agencies.

With the aim of achieving this goal, the Association of Laser Users (AILU) has partnered with the recently-launched EPSRC Centre for Innovative Manufacturing (CIM) in Laser-Based Production Processes. Resources have been pooled to provide leadership and organisational structure to coordinate inputs from both industrial and academic sectors of the UK community in laser-based manufacturing applications with the aim of generating such a Roadmap. In addition, we are pleased to acknowledge the support of the Department for Business, Innovation and Skills (BIS) and the Electronics, Sensors and Photonics Knowledge transfer Network (ESP KTN).

Objectives

The primary *purpose* of the Roadmap is to identify new and evolving ***manufacturing applications*** where laser processing may play a significant enabling role, e.g. for high-value-added components fabricated from new/mixed engineering materials, or relating to new production techniques.

In addition, the aim is to identify relevant areas where ***future research and development*** would be required to facilitate laser-based solutions to such production needs, for example in new laser-material process science and technology, new or enhanced laser source development, beam manipulation and delivery and integration/control issues.

Consequently, the Roadmap output should provide foresight information relating to one or more of the following:

1. new or enhanced manufacturing processes and/or applications:
2. new or enhanced laser-based manufacturing systems;
3. new or enhanced key system components (e.g. new lasers)

UK industrial laser source and system manufacturers continue to suffer from a relatively weak home market, driving them to export typically >80% of their products. Indeed, it is relevant to note (and react to) the fact that photonics-based technologies were nearly-completely absent from the view of the future of UK manufacturing produced in a report [1] produced in late 2012 by a Foresight Team working with the UK Government Office for Science. So, whilst fully recognising the global nature of the business an important objective is to alert UK manufacturers and government industrial policy makers to the powerful enabling features of laser-based processes in manufacturing across diverse sectors of industry, and particularly at the high-added-value end of the market.

One-Day Roadmapping Workshop

A critical element in the formulation of a UK Roadmap covering Laser-based Manufacturing Applications is the *1-Day Roadmapping Workshop* scheduled to take place on 04 March 2014 at the BIS Facility in Victoria St, London. This Roadmapping Workshop has been planned in close consultation with the Institute for Manufacturing (IfM) at Cambridge University, and particularly with Dr Nicky Athanassopoulou, who will provide facilitation on the day.

The experience of IfM professionals with this type of Workshop strongly suggests a limit for on-site participation of about 30, and this matches the available facilities which are provided by BIS. Faced with this difficult selection task, the organising team has sought to produce an attendee list which is dominated by industrial colleagues (>4:1 of industry/academia), has a good balance between users and those in the hardware supply chain, and includes a good experience balance.

Moreover, recognising that with such a small number of delegates there will be many with much to offer the Roadmap construction process who will not be present on the day, we are including non-attendees and attendees alike in a ***pre-Workshop 'Homework Stage'***, so that a significantly larger fraction of the UK LMP community can contribute. Further information including guidance notes and *pro-forma* for the pre-Workshop submission are provided below.

We are not, of course, starting from scratch. In addition to the Farnham Report [2] there has been, for example, the Europe-wide Photonics21 Roadmaps [3], to which many in the UK community have contributed.

References

1. '*The Future of Manufacturing: An Era of Opportunity and Challenge for the* UK' Foresight Report from UK Government Office of Science, London (November 2013). Both Main Report and Summary Documents are available at:. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/255923/13-810-future-manufacturing-summary-report.pdf
2. Farnham Report 'First steps of a strategy for Laser Materials Processing in the UK: Report of the UK Laser Materials Processing Strategy Workshop Farnham Castle, Surrey 21 & 22 February 2012' Published by the Association of Laser Users (AILU) August 2012.
3. Main Photonics21 website at: http://www.photonics21.org/
   Particularly see "*Photonics Strategic Multiannual Roadmap" (April 2013)*, and outputs of:
   - Work Group II, *'Industrial Manufacturing and Quality'*, pp35-41, and
   - Work Group VI *'Design and Manufacture of Components and Systems'* pp70-83

   at: http://www.photonics21.org/download/Brochures/Photonics_Roadmap_final_lowres.pdf

Appendix C: Workshop Programme Agenda

09.45	Arrival	
10.15	Welcome, Introductions and Overview	
10.30	Individual presentations on Drivers, Applications	All
11.45	Prioritisation of the most important applications	All
12.30	Selection of top 5-8 Applications	All
13.00	Lunch	
13.45	Break-out Group Work: Explore the selected applications	In Groups
15.30	Identify/Understand the technologies to be developed/integrated	In Groups
16.30	Feedback and Review	All
17.30	Close	

Workshop Objectives

- Identify what applications are emerging in lasers, processes and materials
- Identify what type of lasers or associated equipment will be required by industry in the future
- Identify the capabilities and underlying technologies that will be needed to deliver future laser systems and applications.
- Select and explore applications effectively
- Promote a consensual approach to application prioritisation leading to practical action plans

Appendix D: Attendee Groups for Detailed Exploration of Selected Application Areas

Additive Manufacturing including Repair	Joining materials including both thin and thick, similar and dissimilar materials	Surface processing and modifications	Micro-manufacturing
Clive Grafton-Reed Mark Goossens Jagjit Siddhu Louise Jones Alastair Wilson	Simon Fung Paul Hilton Robert Lamb Nick Longfield Neil Main Stewart Williams	Ric Allott Karen Brakspear Adam Brunton Mike Green Mark Greenwood Duncan Hand Roy McBride	Daniel Esser Malcolm Gower Denis Hall Lin Li John Lincoln Andrew Kearsley Steve Norman Mike Osborne Craig West

UK Roadmap 2014: Laser-based Manufacturing Applications **Consultation**

The primary objective of the UK Laser Manufacturing Roadmapping exercise and report is to identify new and evolving manufacturing **application areas** where laser processing may play a significant enabling role and to identify relevant areas where **research & development** would be required to facilitate future laser-based solutions to such production needs.

In an effort to achieve as large and diverse a set of inputs from across the UK community as possible within a structured set of activities, a multi-step process was conceived as follows:
- 1-Day Roadmapping Workshop and Interim (Draft) Roadmap Report (completed, attached);
- Consultation with the UK Industrial Laser Community (including this document);
- Dissemination of the Final UK Roadmap-2014 Report (by the end of 2014).

This consultation questionnaire is designed to collect your views on the accompanying Draft UK Laser Manufacturing Roadmap Report and the priorities for application areas and research & development identified within it in order to develop the final UK Laser Manufacturing Roadmap report.

Part 1 - Application Areas

The following four application areas were identified as the top four priorities for the UK community at the Roadmap Workshop on 4 March 2014:

A - Additive Manufacturing including Repair
This included netshape and post processing, faster redesign of many components especially for aerospace applications, laser sintering, manufacturing of multi-materials and high speed powder bed fusion AM using combined laser and e-beam build processes.

B - Joining materials including both thin and thick, similar and dissimilar materials
This included welding as a joining process, welding of lightweight structures, ability to weld ultra-high strength steel (UHSS), bonding of dissimilar materials e.g. glass-to-glass, glass-to-composites and sintering of crystalline powders into ceramics, adhesive-free bonding to eliminate contamination and stress-free optical bonding for beam and image transmission.

C - Surface processing and modifications
This included laser texturing thin flexible glass for example to enhance the out-coupling for OLED lighting applications, laser cleaning/ablation technology, and general surface processing and modification applications.

D - Micro-manufacturing
This included micro welding for medical and other applications, cutting of micro tubular components, microfluidics, micro-processing, parts assembly and placement, annealing and marking.

1. Do you agree that the application areas listed above are the top four priorities for the UK community?

◯ Yes ◯ No

2. If you answered ‘No’, please select an application area, either from the list of topics below (i.e. Those identified during the roadmapping process) or in the ‘other’ box, which you think should replace one of the four listed above. If necessary, up to four application areas can be identified to replace all four listed above.

Short Term - within 3 years

- ☐ Manufacture & lead time reduction
- ☐ Better lasers - more power, less cost
- ☐ Improved yield
- ☐ Processing glass/brittle materials
- ☐ Skills and labour requirements
- ☐ Automation for customisation
- ☐ High Precision Manufacturing
- ☐ Big data
- ☐ Composites processing advanced composites

Medium Term - within 5 years

- ☐ Skills and labour requirements
- ☐ Economic, political and regulatory changes in macro environment
- ☐ Reduced energy costs/consumption
- ☐ Social Changes
- ☐ Flexible manufacturing
- ☐ Process composites and complex materials
- ☐ Produce multi-functional structures
- ☐ Reduce manufacturing and laser system cost
- ☐ Mobile/Portable systems
- ☐ Control
- ☐ Re-manufacture
- ☐ High power cold machining
- ☐ Large area processing
- ☐ Opto-electonic applications
- ☐ Material removal
- ☐ Laser processing of composites, advanced materials - basic process and control
- ☐ Laser processing of composites advanced materials - physical scale and shape of part
- ☐ Laser processing of composites and multiple materials

Long Term - within 10 years

- ☐ Improving knowledge transfer
- ☐ Requirement for better fuel efficiency
- ☐ Enabling higher processing speeds
- ☐ Better product reliability and consistency
- ☐ Better integrated laser-based systems
- ☐ New laser processing machines (capabilities)
- ☐ Automation and customisation
- ☐ Integration of processes
- ☐ New manufacturing capabilities and process
- ☐ Nano-manufacture
- ☐ High intensity high power non destructive testing/imaging

Other application area(s) not listed above - please provide details *(max 1000 characters)*

3. If you answered 'No' to question 1, which application area(s) would your suggestion(s) in question 2 replace from the initial list above (A-D)?

☐ Additive Manufacturing including repair

☐ Joining materials including both thin and thick, similar and dissimilar materials

☐ Surface processing and modifications

☐ Micro-manufacturing

Part 2 - Research and Development Priorities

The following technologies and R&D activities were deemed most important by the workshop participants to support the development plans of the laser-based manufacturing applications as well as strengthen the UK research capability as a whole:

A. Fundamental understanding of laser-material interaction
Improve the fundamental understanding of laser-material interaction and eliminate the "black art" currently associated with laser-based manufacturing processes. In particular, understanding and controlling material and / or join distortion, heat profiles, gas shielding, microstructure and residual stress for a range of materials were regarded as very important. Furthermore, research in material science of dissimilar or advance materials was also considered a critical long term goal.

B. Process output monitoring, analysis and control
Process output monitoring, analysis and control were regarded as of key importance in this field. This incorporates process modelling, porosity control, process development for high average power applications, processing of multiple materials as well as process synchronisation and / or parallel processing. Ultimately, full integration of different laser processes and subsequent integration of laser processes with other manufacturing processes is required to advance this area. This needs to incorporate sensors to enable the development of faster response systems by a factor of 10 or more with the ability of real-time data processing and control.

C. New lasers and laser systems
Better or new lasers and laser systems are required for the new manufacturing processes and applications. This includes, faster (picosecond and femtosecond), higher power, lower cost, more reliable lasers capable of continuous operation. Integration of lasers into machines, tools and equipment is also required and this needs to be supported by an improvement of the quality and availability of laser consumables.

D. Beam delivery and control
Beam delivery and control is currently an issue for many laser-based manufacturing processes. Beam shaping can inadvertently affect precision and speed. Better beam characterisation, diagnostics and manipulation, possibly with the inclusion of adaptive optics are necessary to allow wider use of lasers in manufacturing.

E. New scanners and scanning systems
Development of sophisticated, high speed scanners and scanning systems is also a priority in the field.

4. Do you agree that these 5 R&D areas identified during the roadmapping process are the most critical to delivering progress in the application areas listed in the previous section?

◯ Yes ◯ No

5. If you answered ‘No’, please select an R&D area, either from the list of topics below (i.e. Those identified during the roadmapping process) or in the ‘other’ box, which you think should replace one of the five listed above. If necessary, up to five R&D areas can be identified to replace all five listed above.

☐ Closed loop system

☐ Modelling

☐ Expert systems

☐ Shielding systems

☐ Laser peening

☐ Laser polishing - for additive manufacture parts

Other R&D area(s) not listed above - please provide details *(max 1000 characters)*

6. Which R&D area(s) would your suggestion(s) in question 5 replace from the list above (A-E)?

☐ Fundamental understanding of laser-material interaction

☐ Process output monitoring, analysis and control

☐ New lasers and laser systems

☐ Beam delivery and control

☐ New scanners and scanning systems

7. If you suggested a new application area (in question 2), are there any additional R&D areas that are critical to delivering progress in this area? *(max 1000 characters)*

Part 3 - General

8. Do you have any general comments on the content of the report? *(max 1000 characters)*

9. Do you have any further comments or suggestions? *(max 1000 characters)*

Please return your completed questionnaire to **LbPP@hw.ac.uk** by Friday 29th August 2014.

Your details

Name

Company/Affiliation

E-mail address